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Transient Heat and Mass Transfer Analysis of Supercritical Cryogenic Storage Systems with Spherical Static Heaters

FINAL REPORT

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Prepared by:

R. N. Eberhardt
B. K. Larkin
H. R. Richards

Martin Company
Denver, Colorado
Aerospace Division of Martin-Marietta Corporation

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SUMMARY

The problem of heat and mass flow in a single phase cryogenic storage system has been treated. During the course of the project, equations describing the system were developed, thermodynamic and transport data were assembled, and a Fortran computer program was written to solve the problem. Fluids which were considered were oxygen, hydrogen and helium. It was intended to make the computer program general. In this regard, the program can accomodate any vessel geometry; both fluid withdrawal rate and input heat leak may be arbitrary functions of time. Although the program is relatively complex, the supporting theory is relatively simple. The theoretical concepts which were employed are: conservation of mass, conservation of energy, and Fourier's Law for heat flow.

To test the Fortran program, the performance of an oxygen supply sphere was studied. Of the initial charge of 27 lbs. of LOX, nearly 2 lbs. were vented, 23.6 lbs. were supplied, and 1.4 lbs. remained in the sphere at the end of the mission. Fluid temperatures varied from 198° to over 450°R. Pressure increased from 80 psia to 1000 psia in 786 min. During the supply period, pressures varied ± 75 psi about the control level of 900 psia. About 1500 Btu of electrical energy were delivered to the heaters in order to maintain pressure. These results indicate that the program is operational.

INTRODUCTION

The storage and supply of cryogenic fluids is important in several areas of the space program. For example, consider the use of static electrical heaters to supply hydrogen and oxygen to a fuel cell system at pressures within a specified interval. Design of such a cryogenic storage system requires a detailed thermodynamic analysis. Included in such an analysis would be temperature profiles through the stored fluid, heater surface temperatures, pressure, and heater requirements. The underlying theory is not difficult, but its application is very tedious. Fortunately, the problem may be solved by digital computing methods -- so that detailed designs are neither difficult nor expensive.

The purpose of this report is to describe the development, check-out, and use of a digital computer program suitable for design of a cryogenic storage system. Stored fluids may be oxygen, hydrogen or helium. A description of the storage system is given in the Statement of Work, Appendix A.

A word of caution seems to be in order concerning the use of this program. The results, even though they are produced by a computer, should be examined critically. It is not at all difficult to input an incorrect data card. The theory, contained in the program, may not always apply to a real system because of mixing effects. The thermodynamic and transport data used in the program may contain significant errors.

TECHNICAL DISCUSSION

Theoretical Developments

Heat flow is assumed to occur either by conduction or by radiation. The Fourier law expression for conductive flow is

$$\dot{q} = - kA \frac{\partial T}{\partial x} \tag{1}$$

where the symbols are defined in the Nomenclature section. Only rarely can (1) be solved for a real system and it is a common expedient to use finite difference approximations of (1).

The theory of difference approximations is complicated, and only the important results will be mentioned here. In using finite differences, one divides a physical system into n volume elements (nodal points). The larger n becomes, the better will be the degree of approximation to the solution of (1). Practical considerations such as computer budget and required design accuracy place the upper limit on n. For the simple system depicted in Fig. 1 the finite difference approximation to (1) for heat flow from element one to element two is

$$\dot{q}_{12} = kA \frac{(T_1 - T_2)}{\Delta x} \tag{2}$$

The conductance, K_{12}, is $kA/\Delta x$ and may be used to simplify (2) as

$$\dot{q}_{12} = K_{12} (T_1 - T_2) \tag{3}$$

For conductive flow in solid elements in the system, K is assumed to be constant and must be input on the 200 type data card (see Input Instructions below). Because of the extreme changes in pressure and temperature,

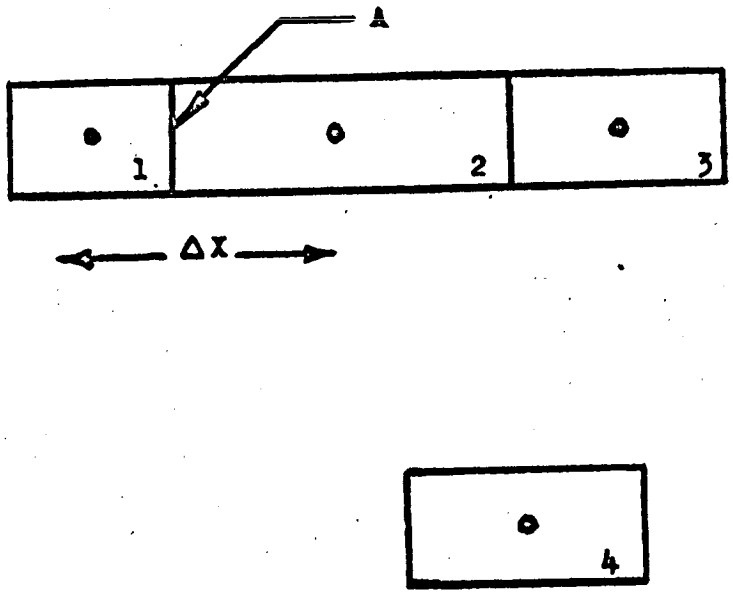

FIGURE 1 AN ILLUSTRATION OF FINITE DIFFERENCE APPROXIMATIONS

it is not possible to assume fluid conductivity as constant. Thus the fluid conductances are computed point-by-point. It is necessary to input the $A/\Delta x$ portion of the conductance, and this is handled on the 201 type data card (see below).

Thermal radiation follows a different relationship and would be written as

$$\dot{q}_{14} = \sigma A_1 \mathcal{F}_{14} (T_1^4 - T_4^4) \tag{4}$$

for exchange between elements one and four. Computation of the $\mathcal{F}$'s is not always easy but McAdams[1] shows how this may be done. Even (4) may be forced into the form of (3) by defining the radiation conductance

$$K_{14}^* = \sigma A_1 \mathcal{F}_{14} (T_1^3 + T_1^2 T_4 + T_1 T_4^2 + T_4^3) \tag{5}$$

Now the temperature terms in (5) change during computation and this requires point-by-point evaluation of K^*. The constant factors in (5), $\sigma A \mathcal{F}$, are input on the type 202 data cards (see below).

Material balance considerations are necessary and are used in a number of ways. The total balance simply involves

$$M_T = \sum_{\text{fluid elements}} V_i \rho_i (P, T_i) \tag{6}$$

Usually it is necessary to find P such that (6) is satisfied. That is, the fluid mass and temperature distribution over the volume elements is known and then the equation is solved for P. A very simple trial and error process is employed here. As an initial guess a value P, say P_1, is used in (6) and this provides a corresponding mass M_1. If $M_1 > M_T$, the assumed P_1 is too large and a fixed increment, say 1 psi, is subtracted from P_1 to

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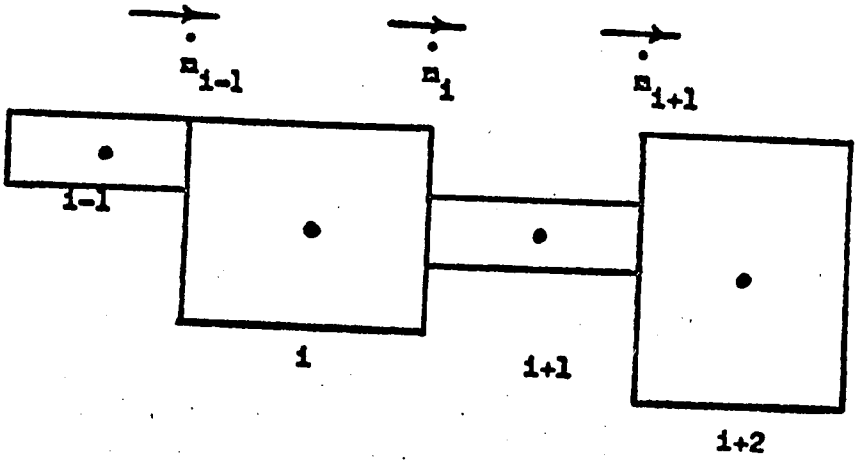

FIGURE 2 A "LINEAR" CONFIGURATION

Two forms of the energy equation are used -- one allowing for mass transfer, (9), the other allowing for no mass transfer. The former case can handle only unidirectional systems while the latter can handle any geometry. For an element of fixed volume, and neglecting flow, the energy equation is

$$M_i \frac{dE_i}{dt} = \sum_j \dot{q}_{ji} + F_i \tag{10}$$

and

$$H_i = E_i + PV_i/M_i \tag{11}$$

The use of (11) in (10) gives

$$M_i \frac{dH_i}{dt} = \sum_j \dot{q}_{ji} + F_i + V_i \frac{dP}{dt} \tag{12}$$

For real fluids enthalpy depends on both pressure and temperature and

$$dH = C_p dT + C_T dP \tag{13}$$

The form of the energy equation as used in the program is obtained by using (13) in (12) and replacing M_i by $V_i\rho$.

$$V_i\rho C_p \frac{dT_i}{dt} = \sum_j \dot{q}_{ji} + F_i + (1 - \rho C_T) V_i \frac{dP}{dt} \tag{14}$$

In order to maintain consistent units a conversion factor, allowing for equivalence between heat and mechanical energy, must be used in the last term of (14).

When mass flow is included, the energy equation becomes more complicated, see Appendix E for details.

$$V_i\rho\frac{dE_i}{dt} = \sum_j \dot{q}_{ji} + F_i + \dot{m}_{i-1} (H_{i-1} - E_i) + \dot{m}_i (E_i - H_i) \tag{15}$$

By means of (11) and (13), it is possible to introduce variables P and T into (15).

$$V_i \rho (C_p - RZ - RTZ_p) \frac{dT_i}{dt} = \sum_j \dot{q}_{ji}$$

$$+ F_i + \dot{m}_{i-1} (H_{i-1} - H_i + RZT_i) - \dot{m}_i ZRT_i - V_i \rho (C_T - RTZ_T) \frac{dP}{dt} \qquad (16)$$

The machine program is designed to solve either (14) or (16). Besides these options it may also treat the case of a perfectly mixed fluid. This situation would prevail if an agitator were used in the storage system. The completely mixed state is the same as (14), but assumes that only a single fluid volume element exists.

Equations (14) and (16) are set up for each volume element in the system and numerical solution is employed. Although these were derived for fluid elements, it should be easy enough for the reader to develop the appropriate forms for solid elements. The equations, regardless of element type, may be placed in the following form

$$C_i \frac{dT_i}{dt} = \sum_j K_{ji} (T_j - T_i) + S_i \qquad (17)$$

where S_i includes all terms on right side of either (14) or (16) except the summation terms. The approximate solution of (17) is

$$T_i (t + \Delta t) = UT_i (t) + \frac{(1 - U)(\sum_j K_{ji} T_j + S_i)}{\sum_j K_{ji}} \qquad (18)$$

where $U = \exp\left(\frac{-\Delta t \sum_j K_{ji}}{C_i}\right)$.

Computation starts at i = 1 and runs consecutively through the nodes with new temperatures being used on the right hand side of (18) as they

are generated. This method is unconditionally stable[2]. Thus the computations will not "blow up" if the wrong Δt is used. However, if the magnitude of Δt is too large, the answers may be seriously in error. The only reliable test of the magnitude of Δt is to run another case with a smaller Δt and check to see that the answers are similar.

Calculation of the dP/dt term requires some discussion. Since this term should contribute only a small amount to the heat balance, the value one time step behind is used. That is, for computing $T_i\ (t + \Delta t)$ we use

$$\frac{dP}{dt} \simeq \frac{P\ (t) - P\ (t - \Delta t)}{\Delta t} \qquad (20)$$

This technique, which has proven to be successful, saves simultaneous solution of the energy and continuity equations. As a result the computer time for a solution is greatly reduced.

A similar procedure is used on the flow terms of (16). At the end of a temperature computation cycle $T_i\ (t + \Delta t)$ is known. The corresponding pressure $P\ (t + \Delta t)$ is found from (6) and (7). But P and T_i determine $\rho_{i,t+\Delta t}$ which in turn determines $\dot{m}_{i,t+\Delta t}$ from (9). These $\dot{m}$ values are supplied to the energy equation and will be used to compute $T_i\ (t + 2\Delta t)$. Thus the cycle is complete. To start the process both dP/dt and $\dot{m}_i$ are assumed to be zero.

At arbitrary times during the mission the contents of the storage system may be agitated, thus eradicating all temperature gradients. This mixing process is one of constant fluid mass and constant internal energy. Contained in the computer program is a subroutine which finds the mixed pressure and temperature. This is a double iteration process since both P_m and T_m are unknown. To begin the solution the initial energy is found from

$$E^* = \sum_{\text{fluid}} V_i \rho_i (H_i - ZRT_i) \qquad (21)$$

and the mass is found from (6). The initial guess for T_m is the lowest temperature in the network. Next P_m is found from (6). Corresponding to the first values of T_m and P_m, the fluid energy is

$$E_1^* = V_T \rho (T_m, P_m) \left[H_m - ZRT_m\right] \qquad (22)$$

Now E_1^* must be less than E^* since the lowest element temperature was used for T_m. On the next iteration cycle the value of T_m is increased by 5°. The cycle is repeated q times, constantly increasing T_m until E_q^* exceeds E^*. At this point T_m is determined by linear interpolation from a formula similar to (7).

Because of the difficulty of treating heat flow in two-phase systems, the analysis begins when the system attains single-phase conditions. If the system is charged with two fluid phases, it is assumed that sufficient time, prior to launch, is provided for the system heat leak to raise the pressure to a single-phase condition. On the other hand, if the system is charged with a single-phase fluid, analysis begins immediately.

Fig. 3, a plot of pressure vs. density, is helpful in explaining the starting process. For the test problem presented in Appendix A the average initial density is 64.5 lb/cu.ft. and fill pressure is 14.7 psia. System heat leak will increase pressure and the fluid will become single-phase at 76 psia. The corresponding saturation temperature is 197°R. These values would be used to start the heat flow analysis.

If the initial conditions were a density of 64.5 lb/cu.ft. and 100 psia, then the fluid is single-phase. Starting values in the analysis would be 100 psia and the corresponding temperature 197°R.

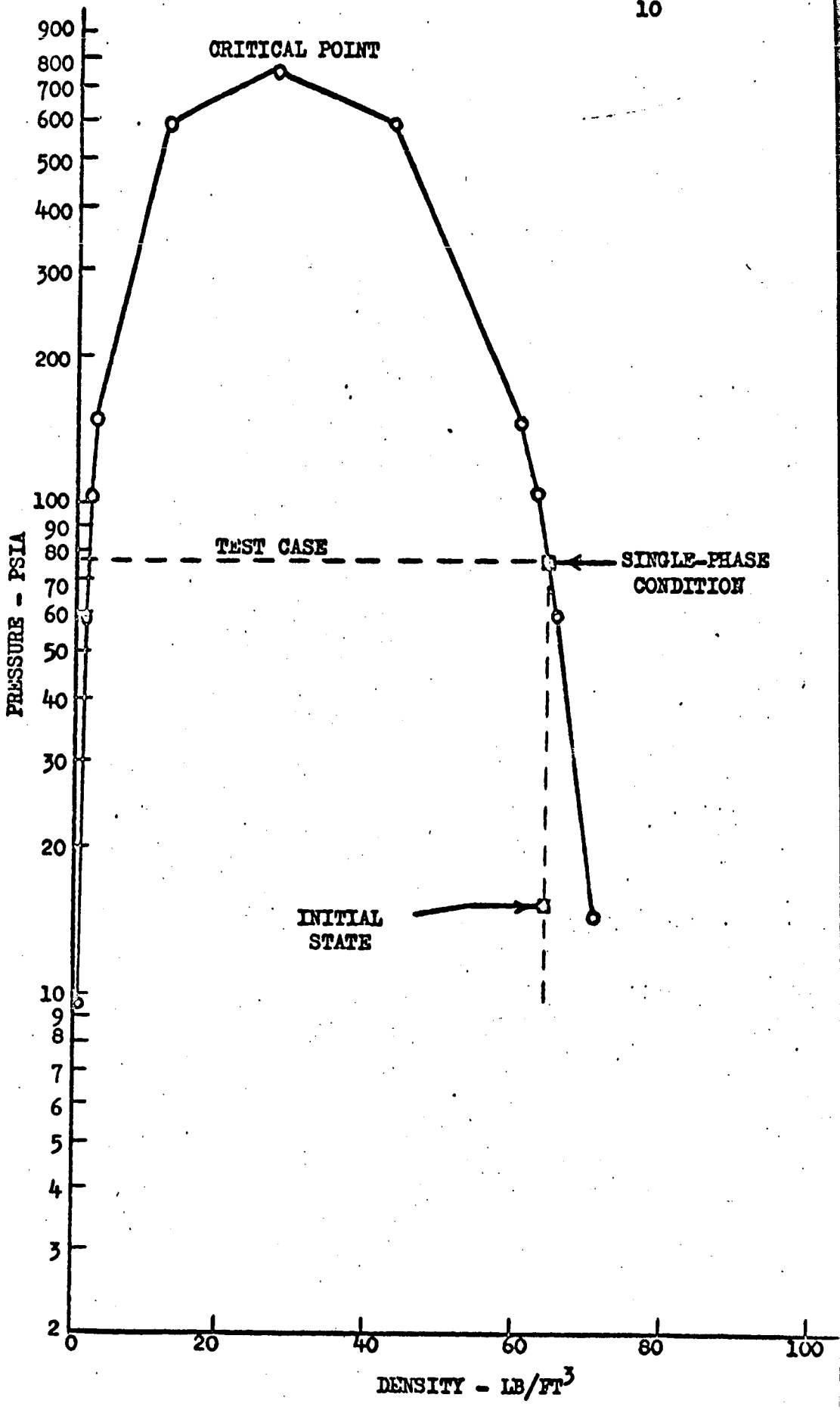

FIGURE 3 OXYGEN SATURATION DENSITIES

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the critical pressure in the pressure vector. Hence the critical values of enthalpy, compressibility, and thermal conductivity will always appear in the two-dimensional array.

It is necessary to pick the initial starting pressure within the bounds of the array, and all resulting machine calculations must be within these bounds.

The number of significant figures given in the tables is not justified on the basis of the uncertainties of the data, but is presented in order to maintain internal consistency.

A listing of the data matrices is included in Appendix C. Also included in Appendix C are the figures based on various correlations which were used to obtain the desired data. (See sections below on oxygen, hydrogen and helium data compilation).

1) Oxygen Data Compilation

The extent of the tables is from the normal boiling point (162°R at 1 atm.) to 1620°R and 100 atmospheres.

The enthalpy data, up to 300°K, was taken from N.B.S. Report 7922[4] and from N.B.S. Circular 564[5] for higher temperatures. The compressibilities were based on density data from Report 7922 and Circular 564.

The lack of accurate thermal conductivity data necessitated extrapolation above 300°K. Figure C-1 shows a plot of data from the compendium[3]. In order to obtain values corresponding to the pressure and temperature vectors, linear interpolation was used to 300°K. The general extrapolation form $y = mx + b$ was used above 300°K. There is an apparent error in the compendium data table. At 73.16°K, well below the normal boiling point,

there is a discontinuity in thermal conductivity from 1 to 20 atm. It is expected that the thermal conductivity for liquids is little affected by pressure. Hence, the conductivity at 1 atm. was assumed the same as that at 20 atm. Although the major area of interest is to 600°R, the extrapolated conductivity data is included to take care of thermal gradients which may show up in the system.

A generalized correlation[6] based on data from the compendium was used to produce values within about 5% of those obtained from extrapolation.

2) Hydrogen Data Compilation

The extent of the data is from the normal boiling point of parahydrogen (36.5°R at 1 atm.) to 990°R and 100 atmospheres.

This compilation is difficult because of the para-ortho conversion. Figure C-2 shows the percent ortho composition at equilibrium with normal hydrogen (75% ortho-25% para) prevailing above 500°R. In practice, the composition is generally unknown. For the data tables, parahydrogen data were used from 36.5°R to 180°R and normal hydrogen values from 270°R and up.

Since both parahydrogen and normal hydrogen values were used in the enthalpy table, it was necessary to use the same enthalpy base for each system. The following relation represents the enthalpy balance that exists

$$H_{normal} = H_{para} + H_c + \Delta H_{base} \qquad (23)$$

H_c is the heat of conversion and ΔH_{base} represents any base difference between the normal and para data sources. The heat of conversion was taken from the compendium[3], and when substituted into the above equation, produced a $\Delta H_{base} = 0$. Hence, the enthalpy data of normal hydrogen taken

from N.B.S. TN 120[7] and Circular 564[5] can be entered in the same table with parahydrogen data from N.B.S. TN 130[8]. For normal hydrogen, TN 120 was used over the temperature range from 270°R to 540°R and Circular 564 was used for higher temperatures.

Compressibilities were based on density data from TN 120[7] and Circular 564[5]. Parahydrogen densities from TN 130[8] differed from normal hydrogen densities by less than 5%. Hence, the accuracy of the data permits the use of compressibility based on normal hydrogen for the entire data matrix.

A P-T-V chart for hydrogen from the compendium supplied the liquid densities. Figure C-3 is a plot of density data extrapolated from TN 120 which agrees well with the P-T-V data of the compendium.

The gaseous thermal conductivity is based on a generalized correlation[6] using 1 atm. data from the compendium rather than a reduced value of thermal conductivity as a reference. The generalized plot produced values for normal hydrogen. Parahydrogen values were obtained from a plot of the ratio of parahydrogen conductivity to normal hydrogen conductivity contained in the compendium[3].

The conductivity of saturated liquid parahydrogen was obtained from the compendium[3]. Since the conductivity of a liquid is little affected by pressure, the saturated liquid values were assumed to prevail at all pressure levels used in the data matrix. It should be noted that the errors in the conductivity data obtained from this correlation may be 30% or more near the critical point.

3) Helium Data Compilation

The extent of the data for helium is from the normal boiling point (7.5°R at 1 atm.) to 1080°R and 210 atmospheres.

Enthalpy data to 100 atmospheres and 600°R was supplied by N.B.S. TN 154[10] with high pressure and high temperature data coming from NASA-Houston[11].

Figure C-4 is a plot of density data used to obtain compressibility factors. Compressibility data from NASA-Houston was used above 100 atmospheres and above 54°R.

The generalized correlation of Gambill[6] was again used for thermal conductivity. The large reduced pressures of the data matrix extended beyond the bounds of Gambill[6] requiring the cross plot shown in Figure C-5. The one atmosphere data compared very well with that of the compendium. Note that the possible errors obtained from the correlation may be as much as 30% or more near the critical point.

Interpolation Procedures

Linear interpolation in a function of two independent variables (pressure and temperature) is equivalent to passing a plane through three tabulated points. Thus the data surface is represented by a series of planar areas -- much like shingles on a roof. This is an impossible representation since it does not allow the data to vary in a continuous manner.

A four point interpolation formula was found to give good results, allowing the data to be represented in a continuous manner over the T-P plane. The theory is illustrated for compressibility factor.

$$Z\,(T,P) = Z\,(T_o, P_o) + a\,(T - T_o) + b\,(P - P_o) + c\,(T - T_o)(P - P_o) \qquad (24)$$

The three points bounding the rectangle whose southwest corner is (T_o, P_o) are used to determine a, b, and c in (24)(see Figure 4).

$$a = \frac{Z\,(T_o + \Delta T,\ P_o) - Z\,(T_o,\ P_o)}{\Delta T}$$

$$b = \frac{Z\,(T_o,\ P_o + \Delta P) - Z\,(T_o,\ P_o)}{\Delta P} \qquad (25)$$

$$c = \frac{Z\,(T_o + \Delta T,\ P_o + \Delta P) - Z\,(T_o,\ P_o) - a\Delta T - b\Delta P}{\Delta T \Delta P}$$

The pressure and temperature at which Z is required is within the rectangle shown on Fig. 4. The quantities Z_P and Z_T may be readily obtained from (24) by differentation.

Because properties may change in a discontinuous fashion at subcritical pressures, four point interpolation is not always possible. This situation prevails whenever the southwest corner point, Fig. 4, is a subcritical diagonal matrix element. For this special case only three points are available and interpolation is effected by passing a plane through these three points.

Note: J and I denote program variables

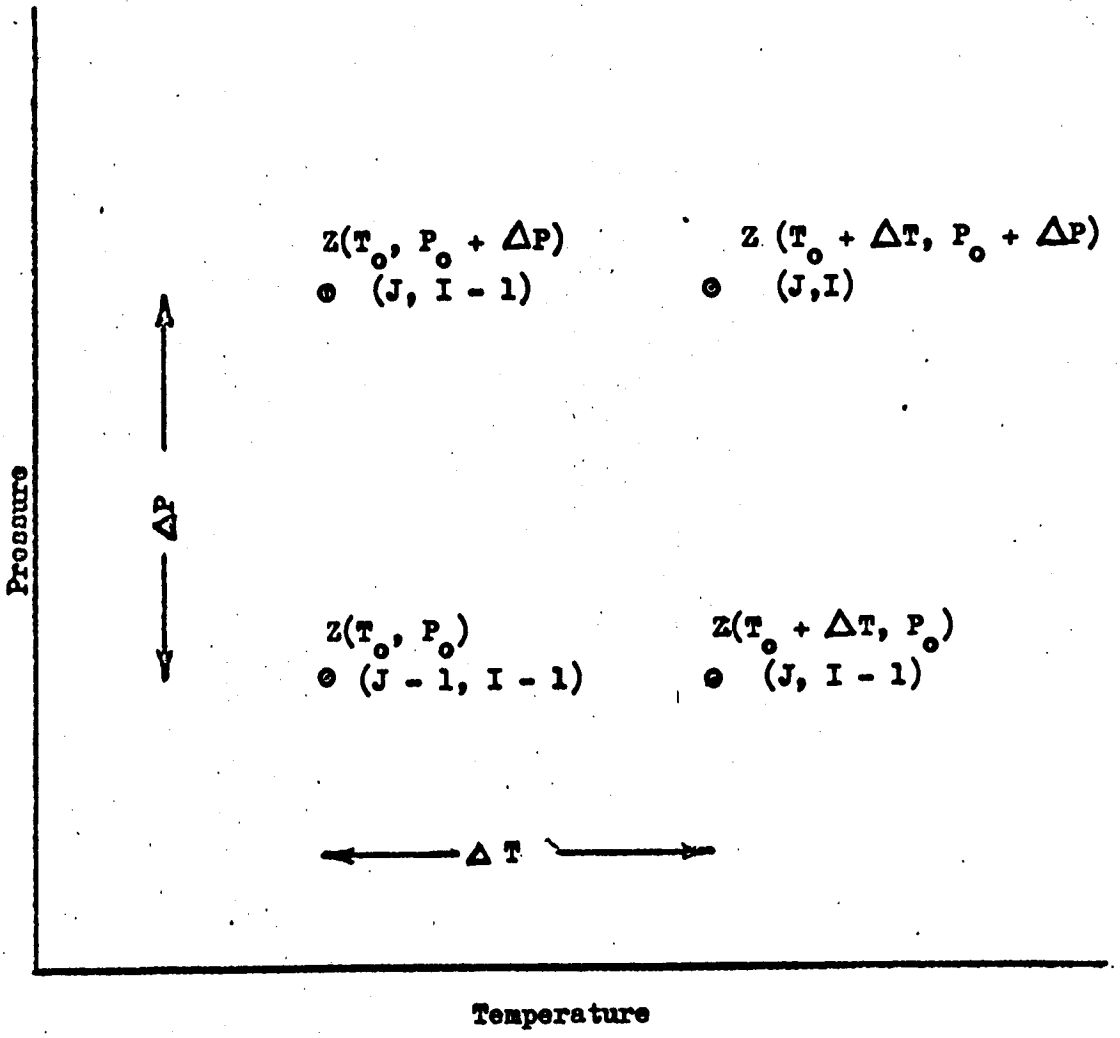


FIGURE 4 INTERPOLATION GRID

PROGRAM DESCRIPTION

General Comments

The above analysis has been incorporated in a Fortran IV computer program. The main part of the program is entitled DORF and this employs subroutines ZOT, DATA, SMERSH and GULCH.

Subroutine ZOT performs the finite difference calculation according to (18). Parameters which must be fixed prior to entering ZOT are the conductor and capacitor values over the network and the heat inputs. From these values ZOT computes a new temperature distribution. ZOT is not needed in the perfect mixing case.

Subroutine DATA is used to generate conductivity, compressibility factor, density, enthalpy, C_p, C_T, Z_T and Z_p from pressure and temperature. Whenever the input pressure or temperature exceed the bounds of the tabulated data, an error message is output and the program terminates.

Subroutine SMERSH and GULCH are very similar. SMERSH generates time varying mass withdrawal rates while GULCH generates time varying heat leaks.

The vectors Jan, Jim, Jack and Jill require some discussion. For a system of arbitrary configuration there will be M volume elements (nodes). Handling such a system on a computer is a tedious procedure, and this procedure will be sketched. The elements are assigned the first M integers as labels and may be in any order (except as noted above for the mass transfer option).

A total of N conductors appear in the network and these are identified, upon input, by the two node numbers which the conductor joins. Although a

pair of node numbers is sufficient to identify a conductor, and program assigns each conductor an identifying number, see Table I. This table is constructed for the sample problem described below.

Table I

Illustration of Jan and Jim Tables

Conductor Index (I)	Jan (I)	Jim (I)
1	1	2
2	2	7
3	2	3
4	7	3
5	3	4
6	4	8
7	8	5
8	4	5
9	5	6
10	6	9
11	7	8
12	8	9

Conductance coefficients, $A/\Delta x$, are stored in XNDR(I) where I corresponds to the index in Table I. These XNDR coefficients are necessary to compute the corresponding conductance values which are stored in the CNDR vector.

Although Table I is sufficient to describe the network, computing time may be reduced by placing these data in another form. The Jack and Jill vectors serve this purpose. Finite difference computations, performed by ZOT, start at node 1 and continue sequentially through all nodes.

Entries in both Jack and Jill are arranged in blocks which are separated by zero. Each block provides conductor and node numbers pertaining to a single node. Table II is a partial list for the data of Table I. Contained in Jack are conductor numbers from the left column of Table I. In Jill are the corresponding node numbers. For example node 1 is joined by conductor 1 to node 2. Thus the entry in Jack is 1 and in Jill is 2. No other conductors join node 1 to other nodes so the block is terminated by a zero. Node 2 is joined by conductors 1, 2 and 3 to nodes 1, 7 and 3, and this comprises the second block in Table II. The program sets-up these tables for the entire network (only results for the first three nodes are shown in Table II).

Table II

Illustration of Jack and Jill Tables

Index, J	Jack (J)	Jill (J)	
1	1	2	Node 1
2	0	0	
3	1	1	Node 2
4	2	7	
5	3	3	
6	0	0	
7	3	2	Node 3
8	4	7	
9	5	4	
10	0	0	

Program Flow Charts

Figs. 5-9 show the logical sequence used in the program. Because of the length and complexity of the program, it is not possible to show every step. The main program begins by reading the network data, sets-up a number of tables, and proceeds through the solution of the program. Subroutines SMERSH and GULCH are not illustrated as they are so simple. Each only involves six Fortran statements.

Input Instructions

In order to solve a storage system problem it is necessary to prepare a number of input data cards. This is a very crucial part of the solution process as key punch errors, out-of-place cards, or decimal point errors will surely cause trouble. Fig. 10 shows the ordering of these cards. Only the last block, the thermodynamic data cards, is supplied with the program cards. All other blocks must be prepared by the program user. Cards within the Network block, with the exception of the 301 cards, may be in any order. See the following list for detailed instructions. Numbers following the definition of input items are IBM card column locations.

DATA CARD 1, FORMAT (I4, 7E10.0)

MWT - molecular weight of fluid in the system, columns 1-4.

QLEAK - heat leak rate into system, BTU/min., average value from fill time to time PMAX is attained, 5-14.

VOLUME - fluid volume of the containing vessel, ft^3, 15-24.

ZASS - total mass of fluid in the vessel, lbs., 25-34.

ZIQMAS - total mass of fluid in the liquid phase, lbs., 35-44.

PZERO - initial pressure, psia, 45-54.

PMAX - system delivery pressure, psia (900 psia in sample problem), 55-64.

TTWO - time at which fluid withdrawal begins for system use, mins., 65-74.

DATA CARD 2, FORMAT (5I4, 4E15.5)

IRMA - number of solid nodes, 1-4.

LYDIA - number of gas nodes, 5-8.

LULU - number of solid conductors, 9-12.

LISA - number of gas conductors, 13-16.

KIM - number of radiation conductors, 17-20.

DTIME - computing time increment for program except as below, min., 21-35.

DTIM - computing time increment while heater is on during main supply phase, min., 36-50.

DELP - pressure span (plus or minus) about PMAX for heater control, psi, 51-65.

FLUX - total heater output, BTU/min., 66-80.

NETWORK DATA CARDS, FORMAT (3I4, 3E15.5, 2I4)

I = 200 signifies solid conductor, 1-4.

LULU NUMBER OF CARDS

J,K Nodes to which solid conductor is connected, 5-8 and 9-12.

XY Conductor value, computed by multiplying the conducting area by the conductivity and dividing by the conductance path length (held fixed), BTU/min °R, 13-27.

XZ = 0.0, 28-42.

YZ = 0.0, 43-57.

(leave last two integers blank)

I = 201 signifies fluid conductor, 1-4.

LISA NUMBER OF CARDS

J,K Nodes to which fluid conductor is connected, 5-8 and 9-12.

XY Conductor length, computed by dividing the conducting area by the conductance path length, ft. (multiplied by the conductivity in the program to obtain a conductor value. The conductivity for the fluid volume is a function of the local pressure and temperature.), 13-27.

XZ = 0.0, 28-42.

YZ = 0.0, 43-57.

I = 202 signifies radiation conductor, 1-4.

KIM NUMBER OF CARDS

J,K Nodes to which radiation conductor is connected, 5-8 and 9-12.

XY Computed by multiplying the gray body view factor times the view area by the Stefan-Boltzmann constant, BTU/min. $^{\circ}R^{4}$, 13-27.

XZ = 0.0, 28-42.

YZ = 0.0, 43-56.

(leave last two integers blank)

I = 300 signifies capacitance values, 1-4.

IRMA NUMBER OF CARDS

J Index on the total number of nodes, 5-8.

K = 0, solid nodes, 9-12.

XY Capacitance of the solid nodes, calculated as the volume of the node times the density of the node by the specific heat of the node, BTU/°R, 13-27.

XZ Fraction of input heat leak entering node J. dimensionless, 28-42.

YZ Fraction of heater output entering node J. dimensionless, 43-57.

(leave last two integers blank)

LYDIA NUMBER OF CARDS

J Index on the total number of nodes, 5-8.

K = 1, fluid nodes, 9-12.

XY Node volume, cu. ft., 13-27.

XZ Fraction of input heat leak entering node J, dimensionless, 28-42.

YZ 0.0, 43-57

(leave last two integers blank)

I = 301 signifies end of capacitor and conductor input, 1-4.

1 Card Only

J Number of time increment steps between printout for pressure rise and venting calculation parts of mission, 5-8.

K Number of elements in STIR vector, see below, 9-12.

XY Maximum pressure for venting during supply part of mission, psia. (For proper heater control XY must be greater than PMAX + DELP), 13-27.

XZ Maximum time allowed for filling and withdrawal (program terminates at this time or when mass becomes 5% of original fill, whichever happens first), 28-42.

YZ -1.0 for complete mixing option, otherwise 0.0 or +1.0. If +1.0 is used, the problem is reset with the mixed pressure and temperature upon exit from Subroutine MIXUP. If 0.0 is used, the problem retains the original temperatures and pressure upon exit from MIXUP, 43-57.

LP Number of time increment steps between printout for supply part of mission, 58-61.

NAN Mass flow option. If NAN is negative, mass flow is computed. If NAN is zero or positive, no mass flow is assumed, 62-65.

STIR VECTOR CARDS, FORMAT (2E20.5)

K NUMBER OF CARDS — STIR (I) - enter the times, in min. at which the MIXUP subroutine is to be entered. The times must be in order and the first should be greater than or equal to TTWO. The last time should be greater than XZ of the 301 card to prevent overrunning of the vector, 1-20.

Leave second number blank.

TIME VARYING MASS WITHDRAWAL CARDS, first card uses Format (I4) and others are Format (2E20.5)

1 Card Only K Number of cards in vectors DOSX and ROSA, 1-4.

DOSX(I) For mission time less than DOSX(I) the mass supply rate is ROSA (I-1). Units are minutes. DOSX(1) is never used and $1 \leq I \leq K$, 1-20.

ROSA(I) Supply rate in units of lb/min. (These are used in Subroutine SMERSH), 21-40.

TIME VARYING HEAT LEAK, first card uses Format (I4) and others are Format (2E20.5)

1 Card Only K Number of cards in vectors PUFF and SPOT, 1-4.

PUFF(I) For time less than PUFF(I) the total system heat leak is SPOT(I-1). Units are minutes. PUFF(1) is never used and $1 \leq I \leq K$, 1-20.

SPOT(I) Total heat leak in units of BTU/min. These vectors are used in Subroutine GULCH. This total heat leak is divided among the nodes according to the XZ entry of the 300 network cards, 21-40.

THERMODYNAMIC DATA CARDS

TEMPERATURE VECTOR, °R	FORMAT (F10.5, I4, 62X, I4)
PRESSURE VECTOR, °R	FORMAT (F10.5, I4, 62X, I4)
HDATA, BTU/lb	FORMAT (8F9.4, 2I4)
ZDATA	
CDATA, BTU/min ft °R	

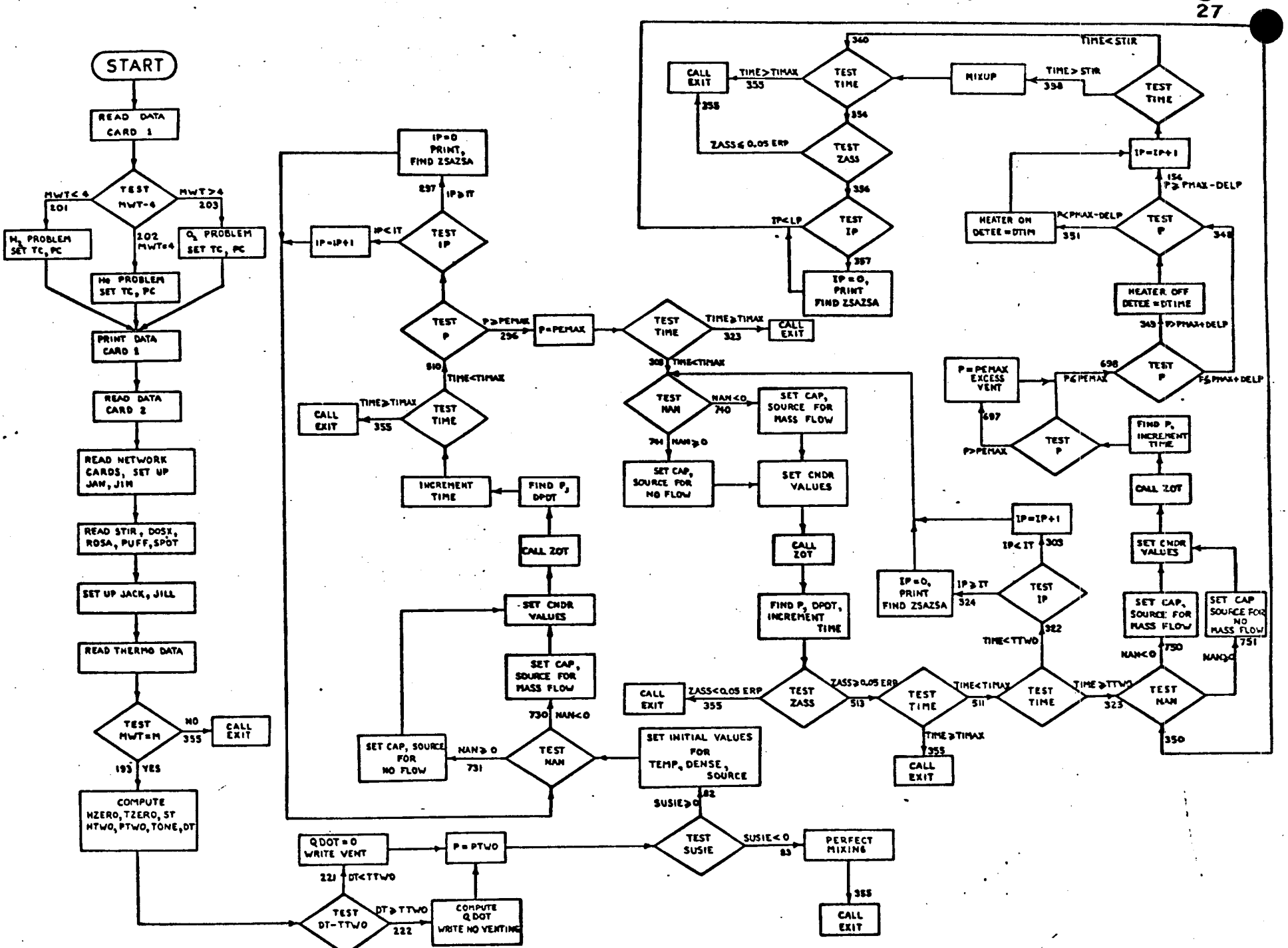


FIGURE 5, FLOW CHART FOR DORF

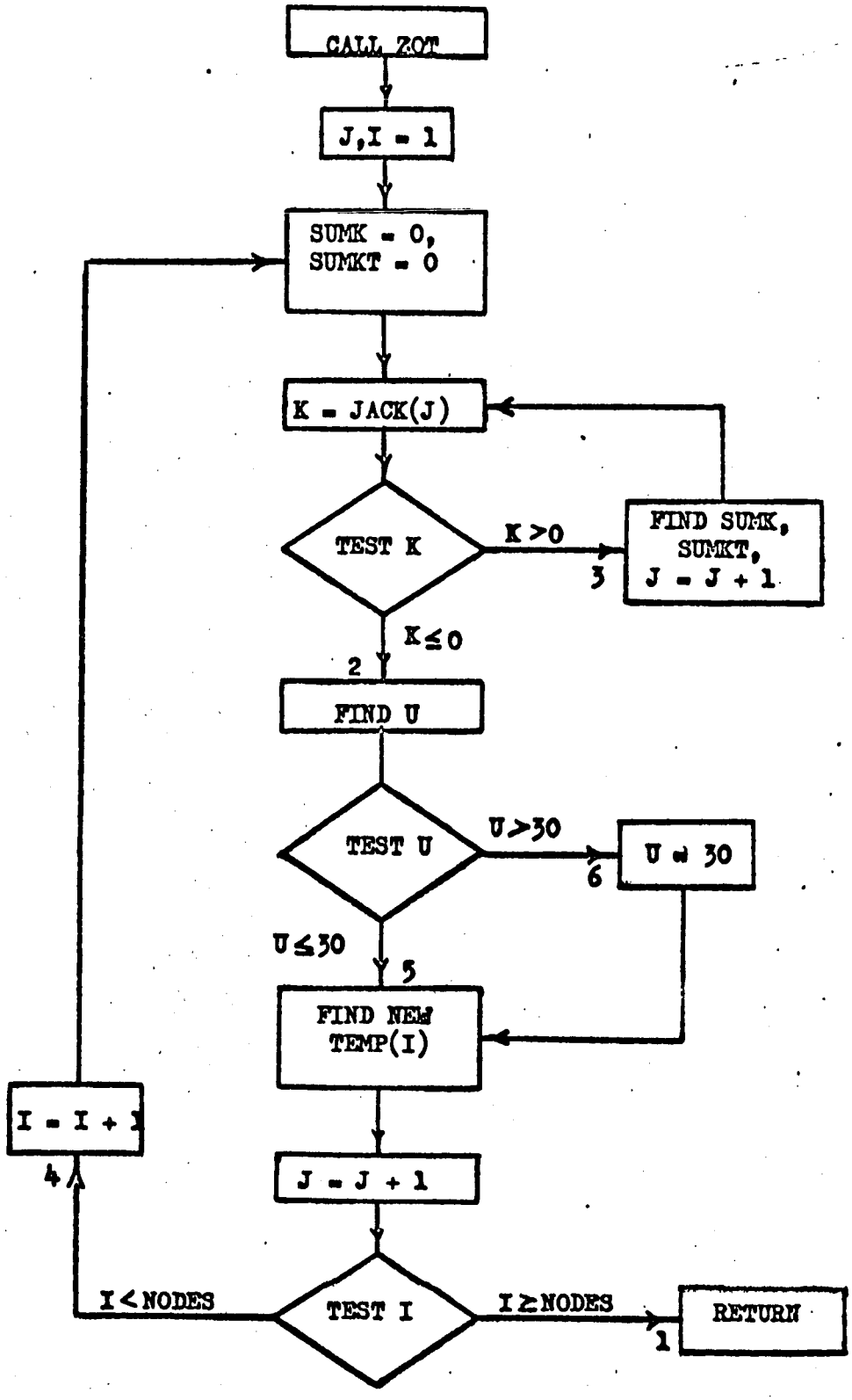


FIGURE 6 FLOW CHART FOR ZOT'

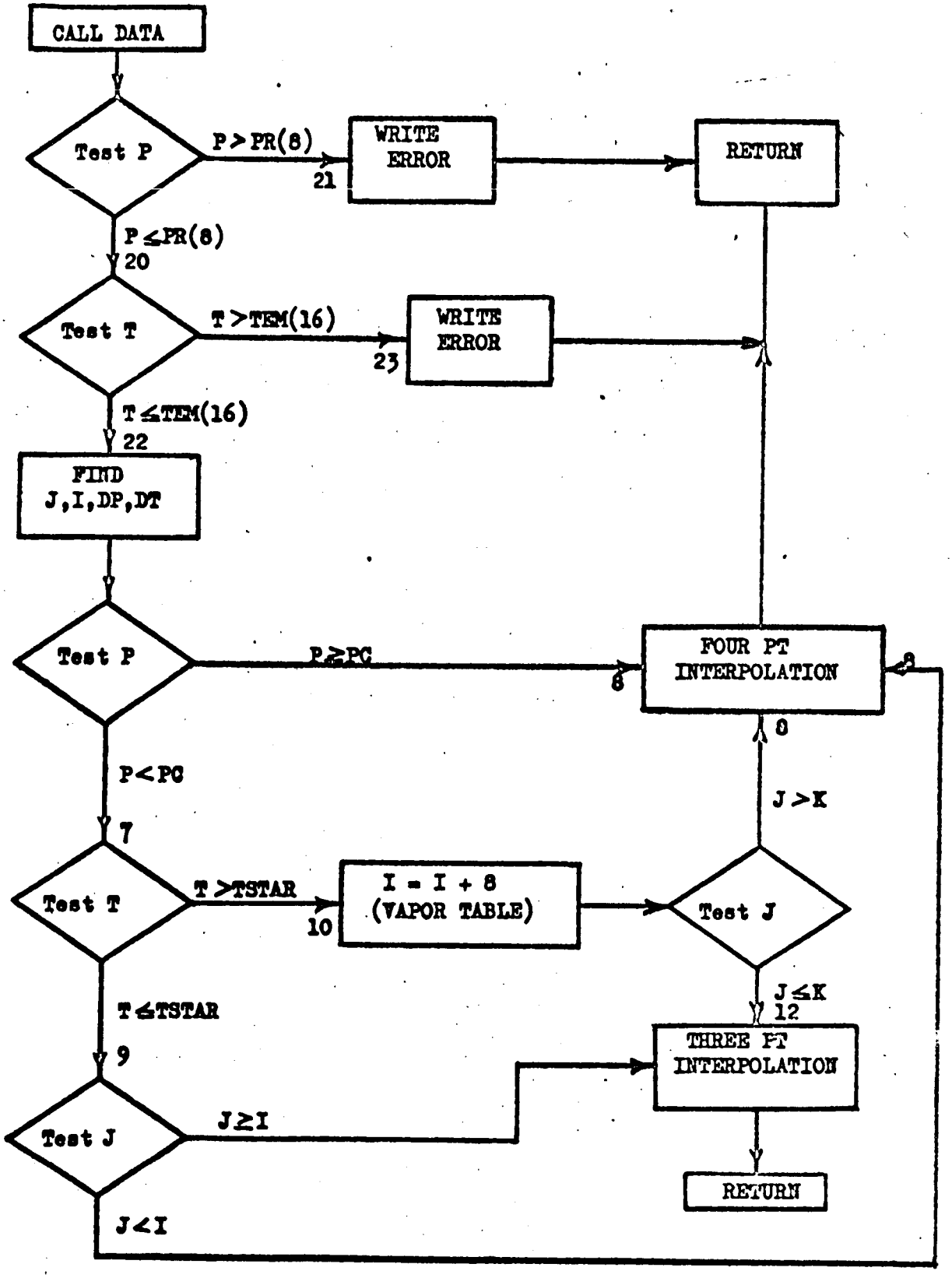


FIGURE 7 FLOW CHART FOR DATA

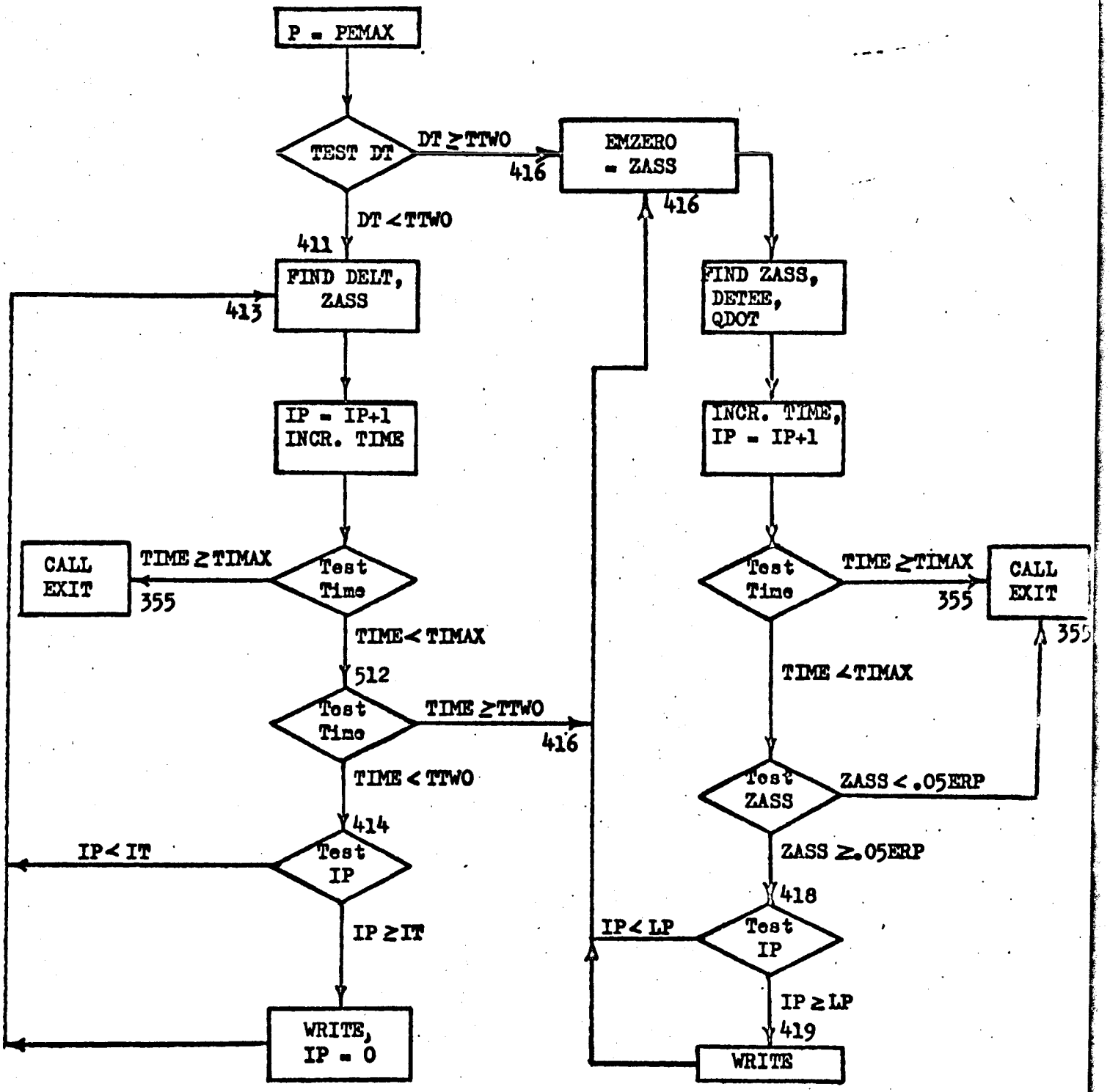


FIGURE 8 FLOW CHART FOR PERFECT MIXING ANALYSIS

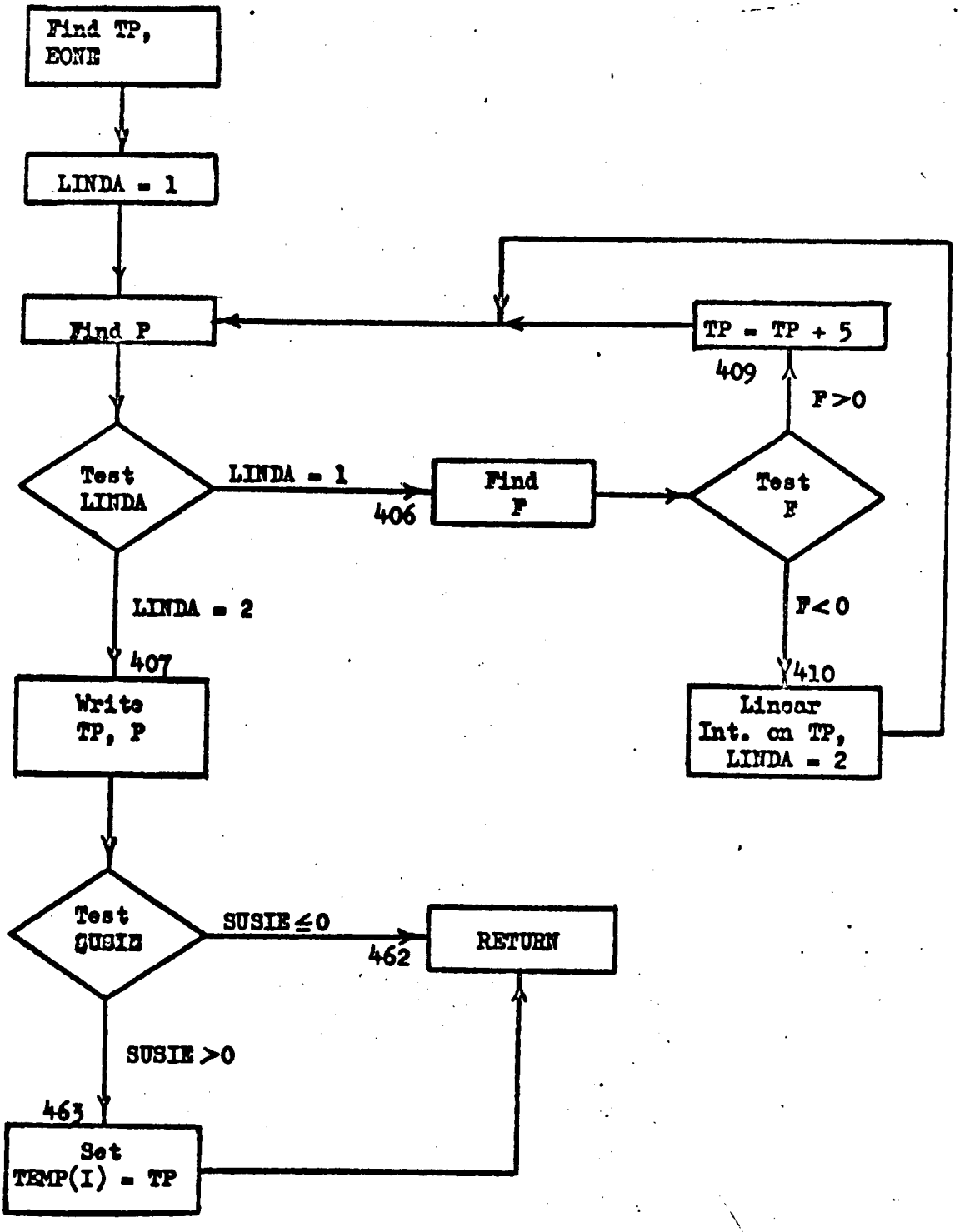


FIGURE 9 FLOW CHART FOR MIXUP

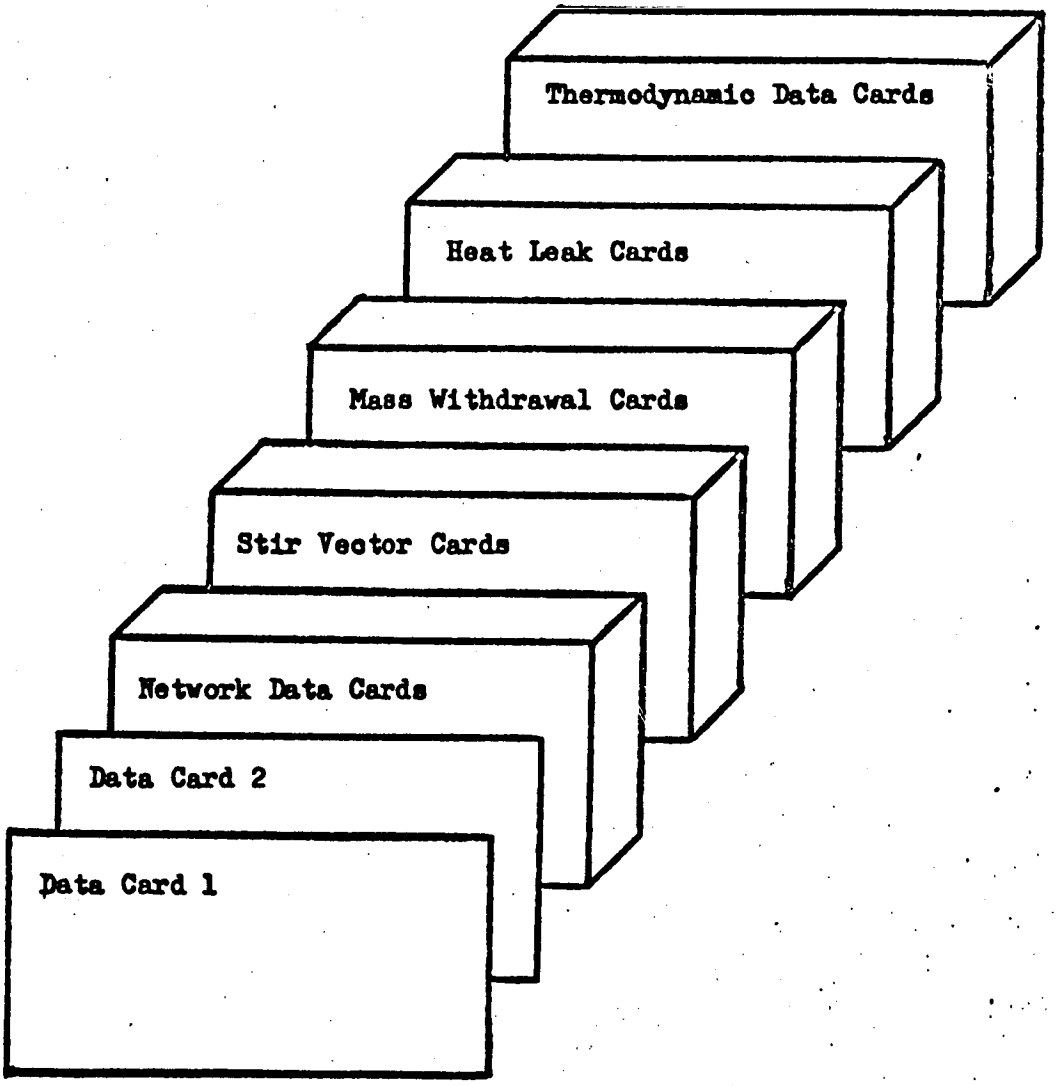


FIGURE 10 INPUT CARD SEQUENCE

SAMPLE PROBLEM

Data Preparation

In order to apply the finite difference portions of the program to the 11.14 in. diameter sphere containing oxygen (see sample problem in Statement of Work, Appendix A), the sphere is partitioned according to Fig. 11, Nodes 1 through 6 are fluid nodes, nodes 7 and 8 are the spherical heaters, and node 9 is the outer shell.

Input is based on the following specified conditions and sample calculations:

DATA CARD 1

MWT - 32
QLEAK 0.061 Btu/min
VOLUME - 0.418 ft^3
ZASS - 26.97 lbs.
ZIQMAS - 26.97 lbs.
PZERO - 14.7 psia
PMAX - 900 psia
TTWO - 11460 min.

} specified for sample problem, Appendix A

DATA CARD 2

IRMA - 3 (nodes numbered 7 to 9)
LYDIA - 6 (nodes numbered 1 to 6)
LULU - 0 (since thickness of heaters is negligible)
LISA - 10 (see Fig. 11 showing the conductors and the nodes they connect)

KIM - 2 (nodes 7 and 8, and 8 and 9 are radiatively coupled; radiation between 7 and 9 due to holes in heater 8 was assumed negligible)

DTIME - 1.0 min.

DTIM - 0.5 min.

DELP - 50 psi

FLUX - 2.0 Btu/min. (problem specification)

Sample calculations for conductor coefficients and capacitance now follow. Consider a conductor coefficient for the conductor between nodes 3 and 4.

XNDR = conducting area/path length

$= 4\pi r_m^2/\ell$ = 9.6 ft.

r_m = 2.850 in. is the mean radius between nodes 3 and 4, see r_4 of the right column of Fig. 11. Now $\ell = r_5 - r_4$ = 0.887 in. where the r's are conductor radii from the left column of Fig. 11.

Thus the coefficient on the 201 data card, Appendix B, which applies to the conductor joining nodes 3 and 4 is 9.6 ft. Ten coefficients must be calculated, corresponding to each of the ten conductors shown on Fig. 11. Nodes 2-3 and 4-5 are connected through holes in the spherical heaters. In this case the conducting area is the area of the holes in the respective heater surface.

Because of the high conductivities of the metal elements in this system, no solid conductors were used.

A corresponding value for radiation is calculated by multiplying the gray body view factor times the view area by the Stefan-Boltzmann constant. Hence, between nodes 7 and 8:

$$XNDR = \mathcal{F} A \sigma \text{ (for convenience } \mathcal{F} = 1.0)$$

$$= 4\pi r^2 \sigma$$

$$= 4\pi \frac{(1.9)^2}{144} \text{ ft}^2 \left(2.855 \times 10^{-11} \frac{\text{Btu}}{\text{ft}^2 \text{min} \cdot \text{R}^4}\right)$$

$$XNDR = 8.99 \times 10^{-12} \frac{\text{Btu}}{\text{min} \cdot \text{R}^4}$$

The capacitance of the solid nodes is calculated as for node 8:

$$CAP = VOL\ (\text{Density})(C_p)$$

$$VOL = \frac{(4\pi r_8^2)(\text{Thickness})}{2}$$

where division by 2 accounts for holes in the heater shell.

$$VOL = (6.28)(3.800)^2(.025) = 2.27 \text{ cu. in.}$$

density = 0.318 lb_m/in^3, C_p = .090 $\text{Btu}/\text{lb}_m \cdot \text{R}$

Therefore $CAP = (2.27)(0.318)(0.090)$

$$= 0.0648 \text{ Btu}/^\circ\text{R}.$$

The volume of the fluid nodes is also needed.

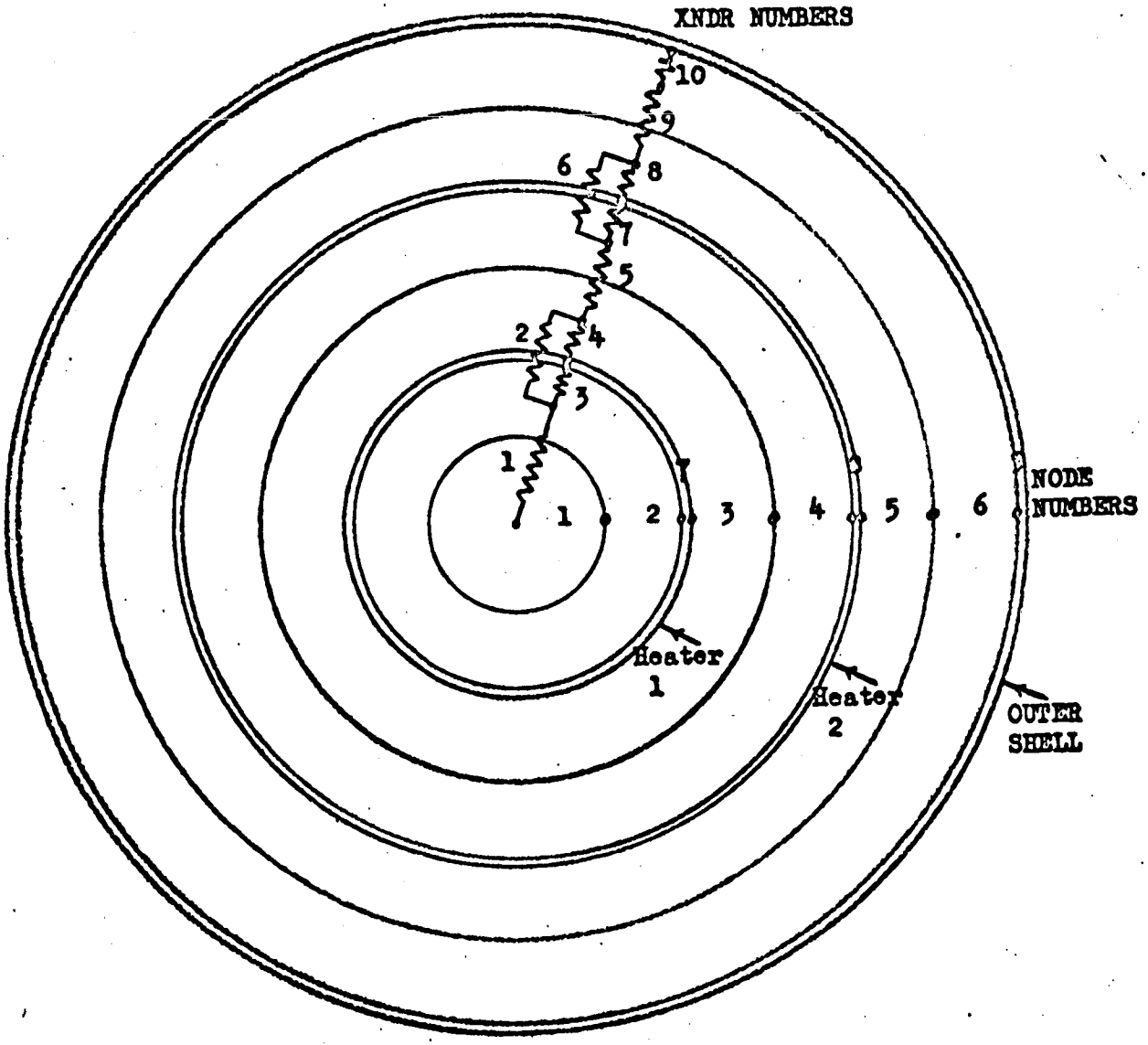
$$VOL = \frac{4}{3}\pi(r_6^3 - r_5^3)$$

node radii $r_6 = 4.685$ in. $r_5 = 3.925$ in.

$$VOL = \frac{(4.1889)(47.960)}{1728}$$

$$VOL = 0.116 \text{ ft}^3.$$

In addition to heat capacity input it is necessary to apportion input heat leak and heater power among the nodes. This apportionment is performed by means of a set of positive fractions of sum unity. For this problem



CONDUCTOR RADII

r_1 = 1.455 in.
r_3 = 1.963 in.
r_4 = 2.438 in.
r_5 = 3.325 in.
r_7 = 3.863 in.
r_9 = 5.127 in.
r_{10} = 5.570 in.

INNER NODE RADII

r_1 = 0.0 in.
r_2 = 0.950 in.
r_7 = 1.900 in.
r_3 = 2.025 in.
r_4 = 2.850 in.
r_8 = 3.800 in.
r_5 = 3.925 in.
r_6 = 4.685 in.
r_9 = 5.570 in.

Fig. 11 OXYGEN SYSTEM NETWORK

the input power fraction for node 7 is 0.2025, and for node 8 a value of 0.7975 is used. No other nodes receive direct input power, thus the input fraction is zero for these other nodes. This set of fractions is listed on the 300 data cards of Appendix B. An identical procedure is used for the input heat leak.

Results

Trial runs were performed using the above input data in order to verify the consistency of the program. Figs. 12, 13 and 14 show results for a test problem.

Fig. 12 shows how fluid mass varies with time for a problem using finite differences and allowing for mass flow between elements. The time required for the heat leak (0.061 Btu/min.) to take the initial charge to a single phase pressure (80 psia) is 6978 mins. It is at this time that the problem really begins. During the period from 6978 to 7760 min., system pressure increases from 80 to 1000 psia while fluid mass is held fixed at 26.97 lb. From 7760 to 11460 min. pressure is held constant at 1000 psia and the mass is reduced to 25.2 lb. by venting fluids. At this time mass is removed at the constant rate of 0.0103 lb./min., as indicated by the constant slope of this portion of Fig. 12. To demonstrate the ability to change supply rate, the rate is increased to 0.02 lb./min. at 13000 min. The problem terminated at 13382 min. when only 5% of the original fluid mass in the system remains.

Fig. 13 shows the temperatures of elements 1, 6 (fluid) and 7 (a heater). During the pressure rise and venting portions of the mission, small temperature gradients exist over the system. For the supply period

element 7, a heater, shows a sharp rise and decay of temperature caused by the on-off control system. Fluid temperatures also rise and decay but with much lower amplitude. Generally, the temperatures show a tendency to increase as fluids are removed.

Fig. 14 shows pressure variation with time. Behavior during pressure rise and venting periods follows the expected variation. During the supply period, fluctuations are observed and these are caused by on-off phases of the supply heaters. Control is such that the heater is on for pressures less than 850 psia and off for pressures above 950 psia. Toward the end of the mission, as the stored mass is sufficiently reduced, pressure fluctuations increase in amplitude. At 13150 mins. the vent pressure of 1000 psia is reached and additional fluid is vented in order to maintain pressure at 1000 psia. The amount vented in this manner is not great, about 1% of the initial charge.

Figs. 15 and 16 show temperature and pressure calculations for the same problem with the exception that no mass transfer effects are considered. General trends for the two sets of calculations are very similar. Slightly greater temperature gradients exist in the latter case, which is no surprise. Electrical input in the former case was 1428 Btu and in the latter case 1482 Btu were consumed. For this problem mass transfer effects do not seem very important.

Fig. 17 shows temperature and heater flux for this storage system based upon calculations assuming perfect mixing within the fluid. Temperatures follow the general trend of Figs. 13 and 15. Flux variations reflect both changes in fluid physical properties and the manner of tabulating

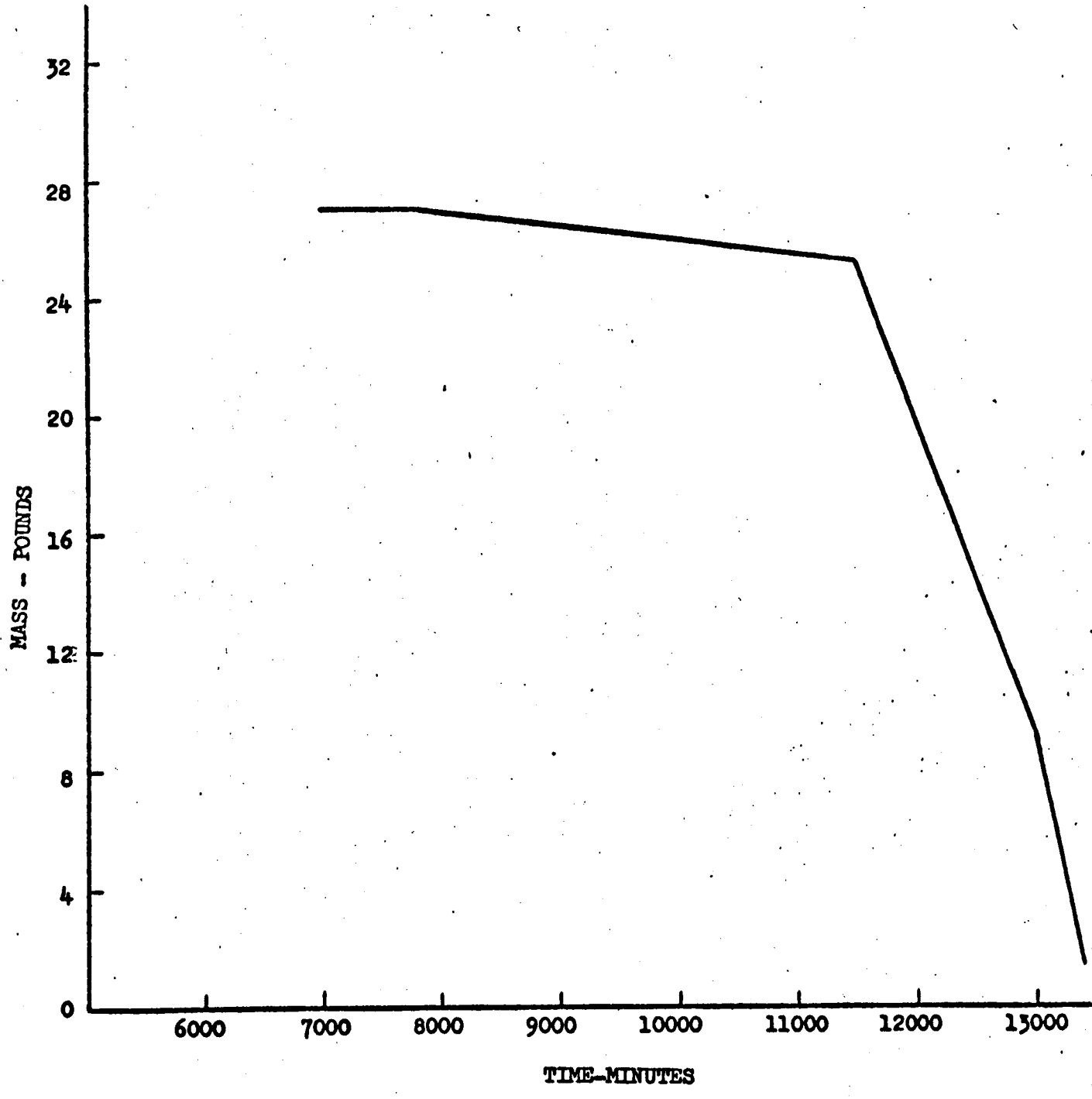


FIGURE 12 STORED FLUID MASS VS. TIME

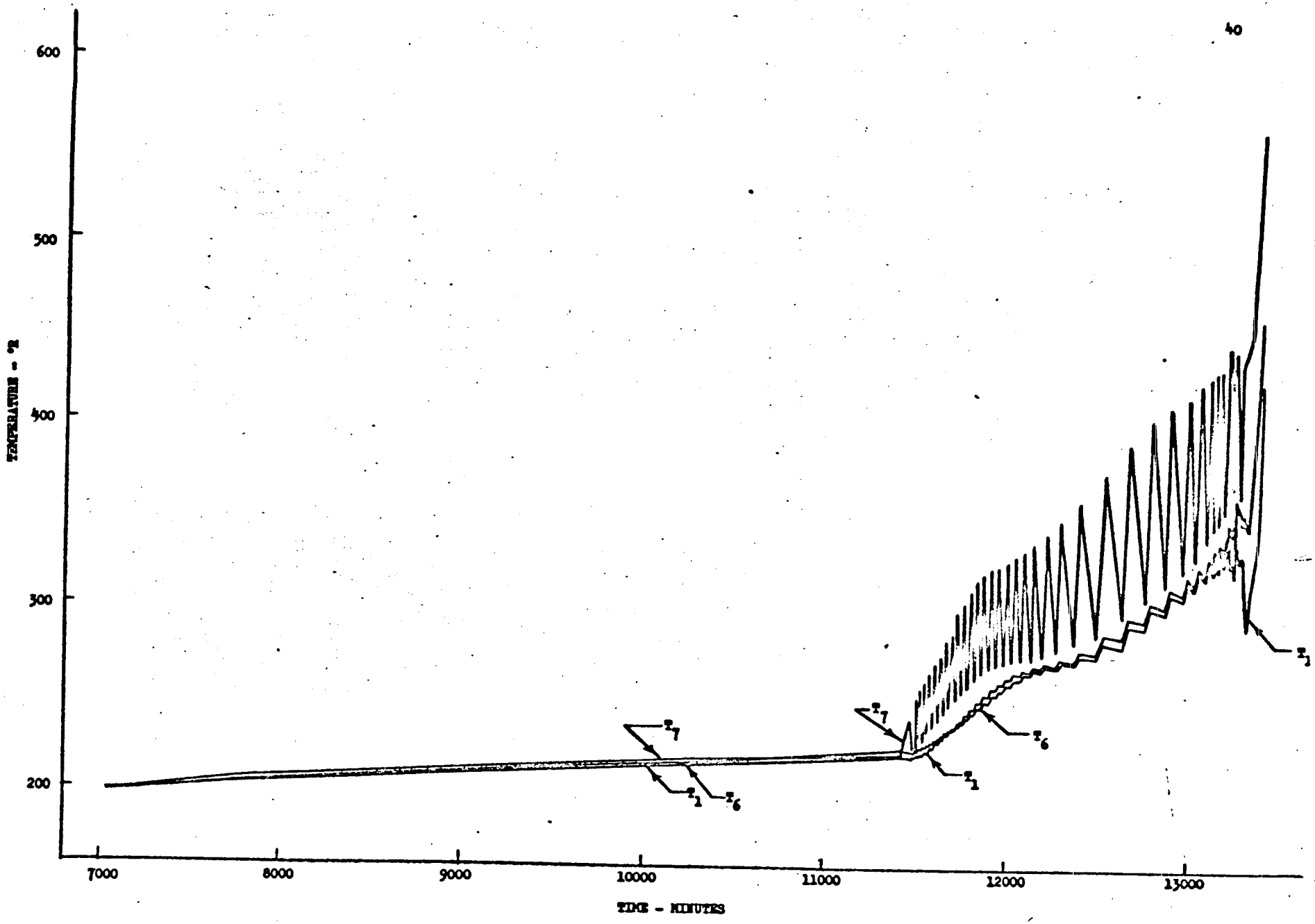


FIGURE 13 TEMPERATURE VS. TIME

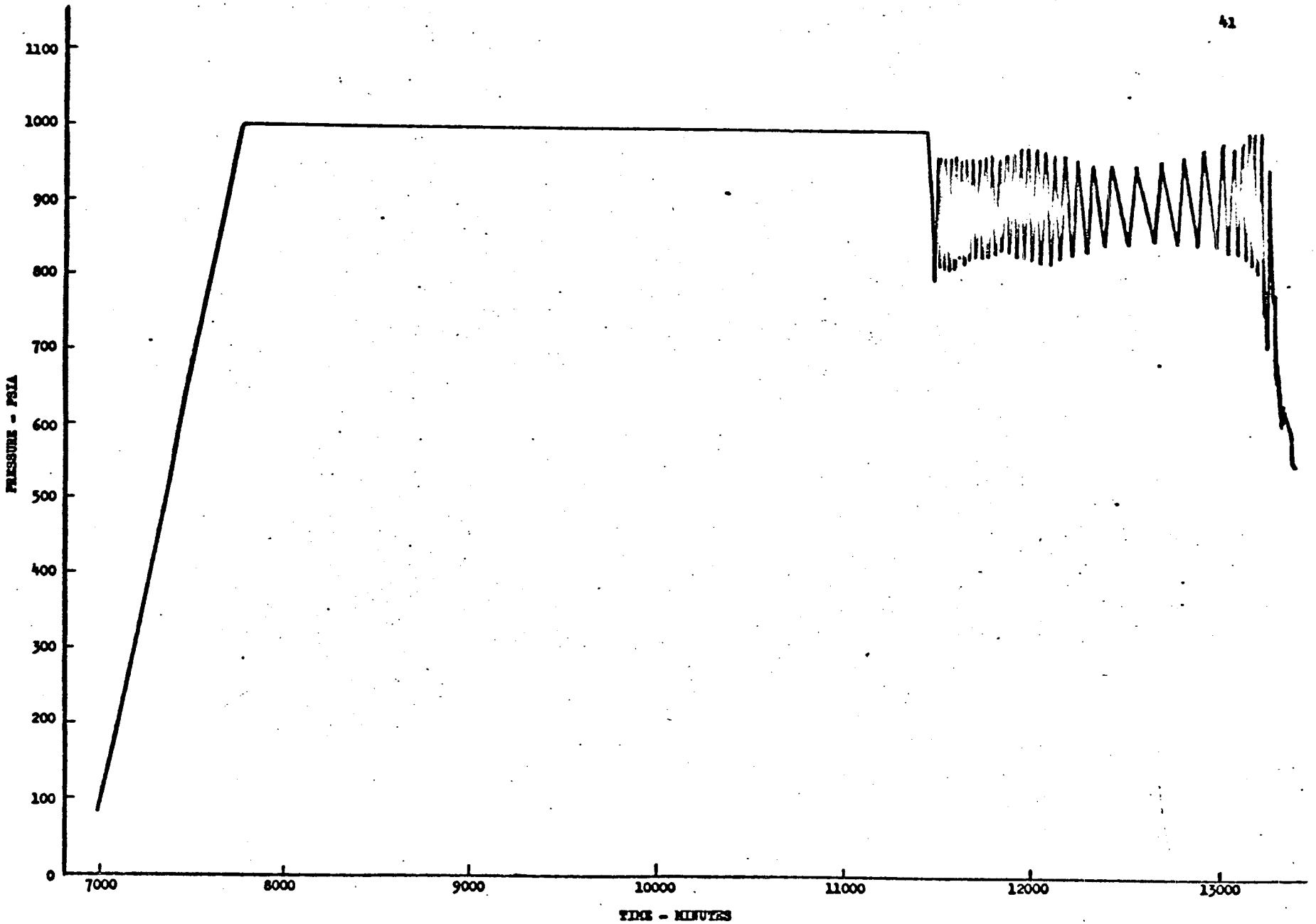


FIGURE 14 PRESSURE VS. TIME

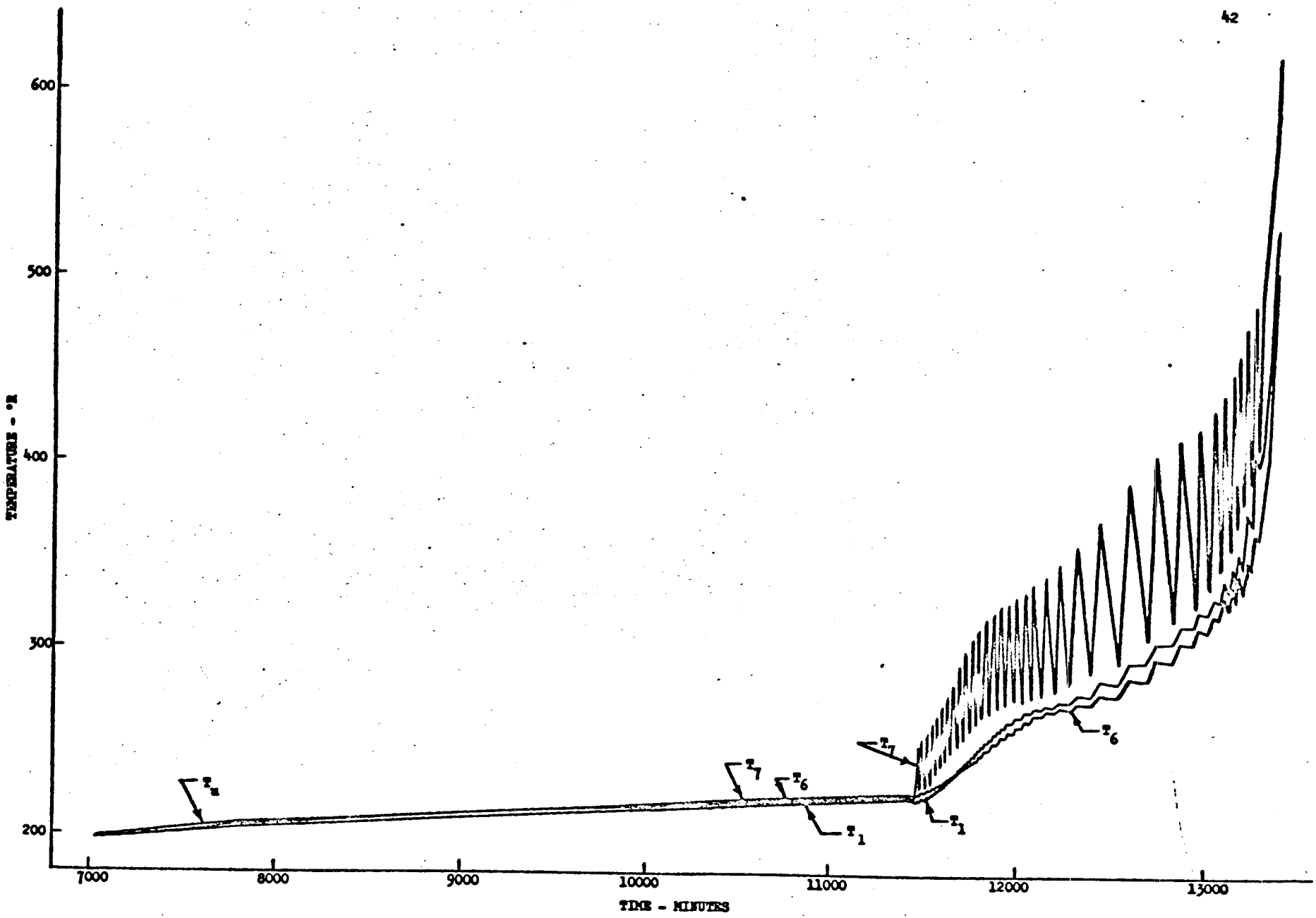


FIGURE 15 TEMPERATURE VS. TIME - NO MASS FLOW

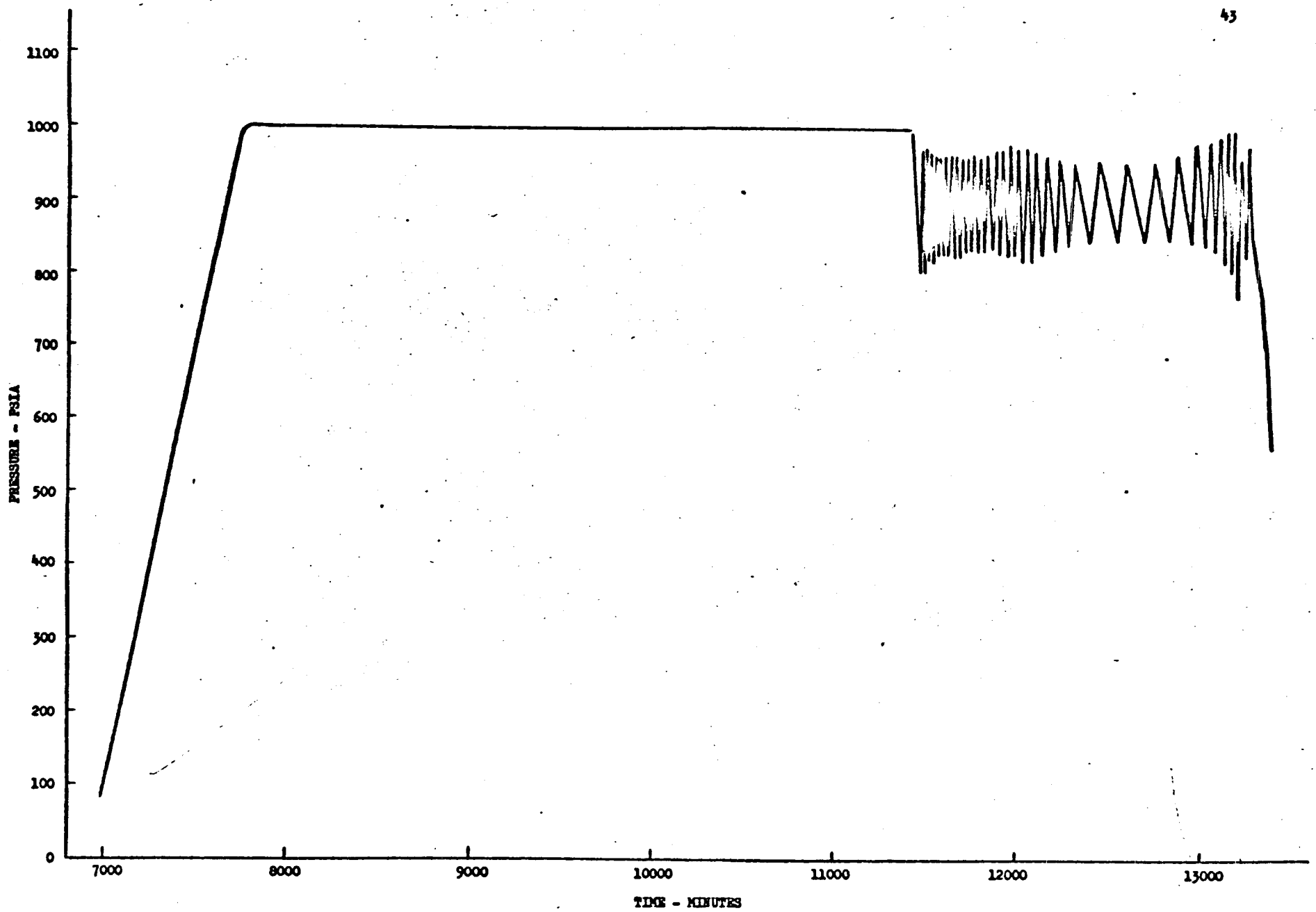


FIGURE 16 PRESSURE VS. TIME - NO MASS FLOW

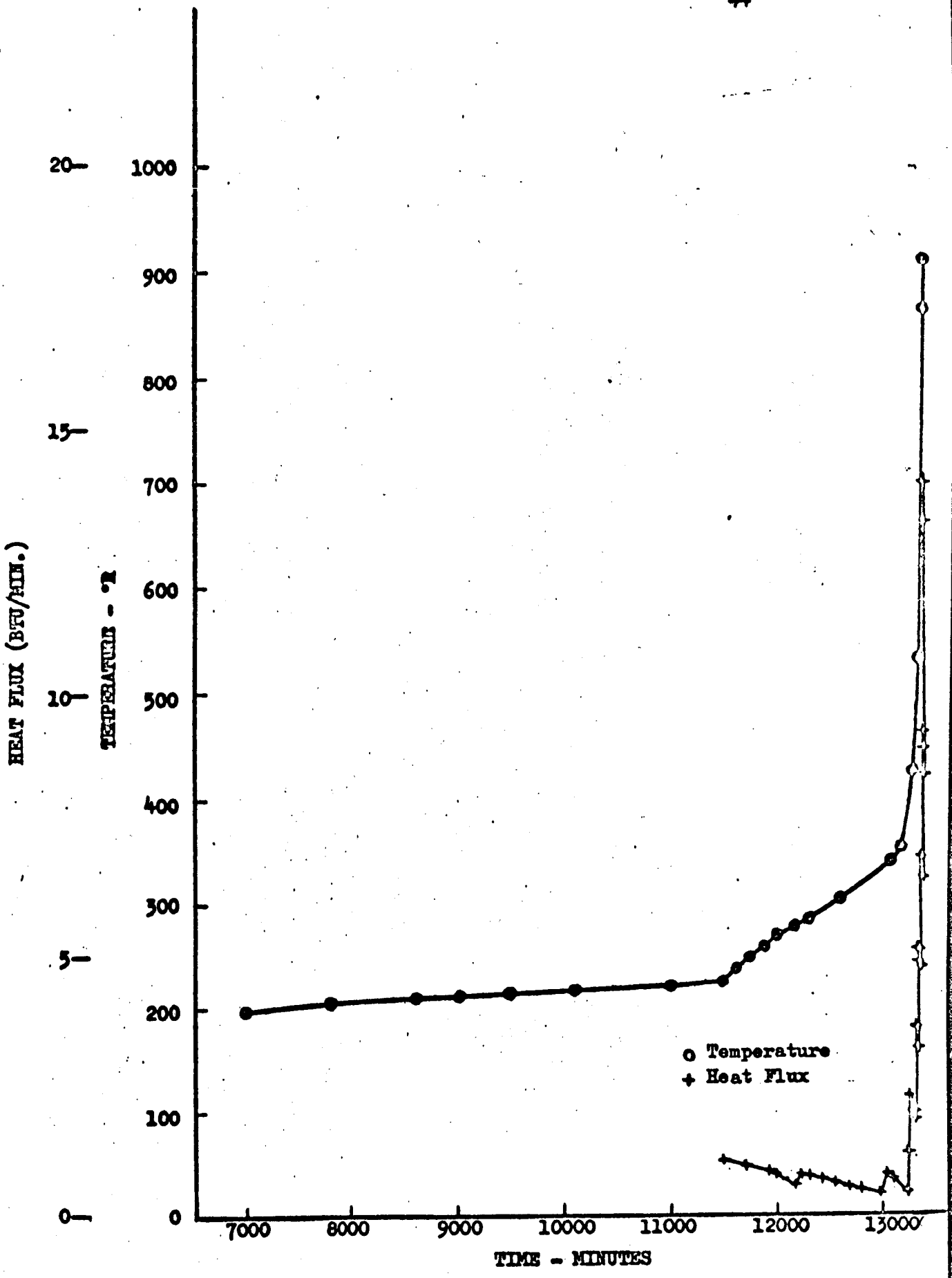


FIGURE 17 TEMPERATURE AND FLUX VS. TIME - PERFECT MIXING CASE

thermodynamic data. The analysis here is different from that used in producing Figs. 13 through 16. Here pressure is mixed and solutions give heater flux. The previous results assume constant heater rating, 2 Btu/min., and solutions give pressure fluctuations resulting from on-off heater control. Electrical energy consumption is 1900 Btu, a somewhat higher figure from those noted above. This higher figure reflects the fact that more energy remains in the system. Fluid temperatures on Fig. 17 reach 900°R while those of Figs. 13 and 15 are on the order of 500°R.

Pressure change from mixing effects are shown in Table III. At the times indicated the adiabatic mixing routine (MIXUP) was called. In every case the mixed pressure was lower than the unmixed pressure. At 12000 min. the most drastic change was noted; it was a drop of 178 psi.

Table III

Pressure Changes From Mixing

Time	Pressure	Mixed Pressure	Mixed Temperature
min.	psia	psia	°R
11500	861	850	225
12000	934	756	265
12500	901	896	284
13000	943	894	321

Output Examples

Tables IV, V and VI show selected output pages from the test problem described in Figs. 12-14. Table IV illustrates the preliminary output as well as the first level of output for the pressure rise portion of the computation. Because of the extensive use of headings, the table should

be easily understood. The first lines identify the storage fluid (oxygen, hydrogen or helium) and some of the input data. If the mass flow option is called, as this problem does, the message "Mass Flow Between Fluid Volume Elements" is obtained. The next line gives the standby time -- time necessary for input heat leak to bring initial charge to a single phase state. Also shown on this line are starting pressure and temperature for the finite difference calculation. If venting is necessary, as is the case here, the time at which venting pressure is attained is shown. Because of mixing effects this is not exactly the same as the time which would be computed by the finite difference technique. If additional heat input is necessary, the amount required would be shown here. Output from the finite difference calculation follows. At each level both time and pressure are shown on a single line. Next the time step criterion is shown (1.24) and the following integer (7) is the node at which this value was obtained. This information might be useful in preparing subsequent problems. For example, by changing the network configuration in the subsequent problems, it might be possible to employ a larger time step. Finally, the temperature distribution is shown.

Table V illustrates output for the venting calculation. Pressure is held fixed at 1000 psia and mass is reduced as the temperature rises. The word "Venting" at the right of the table identifies this mode of operation.

Table VI illustrates output for the supply calculation. The heat flux column shows whether or not the heater is on. If it is on, the entry is the total heater output. If it is off, the entry is zero. The heat input

column gives cumulative electrical energy supplied via the heaters. The excess vent column indicates total fluids vented during the supply part of the calculation. At time 13000.6 min. the program entered MIXUP. The mixed pressure and temperature were found to be 942 psia and 325.9°R, see Table VI. The unmixed pressure, as the table shows, is 973 psia.

Table IV Output Example for Pressure Rise Calculation

Analysis of Supercritical Oxygen System

Heat Leak BTU/Min	Volume Cu.Ft.	Total Mass lbs.	Liquid Mass lbs.	Initial Pressure PSIA	Supply Pressure PSIA
0.06	0.42	26.97	26.97	14.70	900.00

Part I Preliminary Calculations

Mass Flow Between Fluid Volume Elements

Standby Time, Mins.	Starting Pressure, PSIA	Starting Temp. Deg.R
6977.646	80.0	197.76

Vent at 7765.5532 Minutes

Time 7037.6 Min. Pressure 136.3 PSIA

Maximum of DT*SUMK/CAP 1.24 7

Node	Temperature, Deg. R.	Temperature, Deg. F
1	197.91	-261.69
2	197.91	-261.69
3	197.91	-261.69
4	197.94	-261.66
5	198.02	-261.58
6	198.43	-261.17
7	197.91	-261.69
8	198.00	-260.60
9	199.11	-260.49

Time 7097.6 Min. Pressure 205.9 PSIA

Table V Output Example for Venting Calculation

Time 8540.6 Min. Pressure 1000.0 PSIA Mass 26.642 Lbs. Venting

Maximum of DT*SUMK/CAP 1.22 7

Node	Temperature, Deg. R.	Temperature, Deg. F
1	206.74	-252.86
2	207.37	-252.23
3	207.61	-251.99
4	208.51	-251.09
5	208.99	-250.61
6	209.98	-249.62
7	207.54	-252.06
8	208.83	-250.77
9	210.71	-248.89

Time 8600.6 Min. Pressure 1000.0 PSIA Mass 26.617 Lbs. Venting

Maximum of DT*SUMK/CAP 1.22 7

Node	Temperature, Deg. R.	Temperature, Deg. F.
1	207.05	-252.55
2	207.68	-251.92
3	207.92	-251.68
4	208.82	-250.78
5	209.30	-250.30
6	210.29	-249.31
7	207.85	-251.75
8	209.14	-250.46
9	211.02	-248.58

Table VI Output Example for Supply Calculation

Time, Minutes	Pressure, PSIA	Stored Mass, lbs.	Heat Flux, BTU/min	Heat Input, BTU	Excess Vent, lb.
12998.6	979.2	9.266	0.	968.000	0.

Maximum of DT*SUMK/CAP 0.46 8

Node	Temperature, Deg. R.	Temperature, Deg. F.
1	323.15	-136.45
2	343.30	-116.30
3	339.61	-119.99
4	333.46	-126.14
5	330.09	-129.51
6	322.07	-137.53
7	339.74	-119.86
8	331.24	-128.36
9	326.13	-133.47

Mixed Pressure, PSIA	Mixed Temperature, Deg. R.	Time, Min.
942.73	325.9	13000.6

Time, Minutes	Pressure, PSIA	Stored Mass, lbs.	Heat Flux, BTU/Min.	Heat Input, BTU	Excess Vent, lb.
13000.6	973.4	9.245	0.	968.000	0.

Maximum of DT*SUMK/CAP 0.46 8

Node	Temperature, Deg. R.	Temperature, Deg. F.
1	322.92	-136.68
2	342.87	-116.73
3	339.27	-120.33
4	333.10	-126.50
5	329.70	-129.90
6	321.83	-137.77
7	339.17	-120.43
8	330.86	-128.74
9	326.03	-133.57

RECOMMENDATIONS AND CONCLUSIONS

During the course of the project a number of problems were treated in a fashion that left something to be desired. These problems will be ennumerated here, and, hopefully, they can be handled in a more rigorous manner later.

1. The necessary thermodynamic and transport data for oxygen, hydrogen and helium are not available. Conductivity values for helium in the regions of interest were conjured up from a generalized correlation[6]. No single report was sufficient to cover the required range of pressure and temperature -- thus different sources had to be pieced together. It is not difficult to find obvious errors in the Compendium[3]. In view of this situation it is recommended that generous factors of safety be used on equipment designed with these data. Because of the importance of these data, it would be advisable for NASA to acquire and assemble a consistent set of thermodynamic and transport properties for oxygen, hydrogen and helium.

2. Hydrogen exists in two forms -- ortho and para hydrogen. At low temperatures the para form predominates, but at higher temperatures the concentration of ortho increases until the mixture termed "normal" hydrogen is attained. Heats of formation of these species are different, and a thermodynamic analysis of the problem requires a knowledge of the concentration of each species. It was assumed that the conversion from para to normal hydrogen occurred between 180°R and 270°R. If data are available on this problem, it should be incorporated in the data tables.

3. In the analysis it was assumed that only the energy and continuity equations were necessary to solve the problem. The momentum equation was dropped by assuming the pressure to be constant everywhere in the system. This may or may not be a good assumption. Even minor pressure gradients might cause significant fluid motion in low gravity conditions. Since both theory and computers are available to treat this problem, the validity of the assumption should be tested.

4. The program has only been tested for the rather limited problem in Appendix A. A number of other cases should be run to test the program. Problems in hydrogen and helium systems have not been studied.

Because of the nature of this effort -- writing a computer program, the number of conclusions is not very extensive. It seems safe to say that the storage problem can be analyzed effectively via digital computer and that the results will be useful in hardware development and interpretation of flight test data.

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11. Personal communication from Jim Raymer, NASA-Houston to Bert Larkin, Martin Co., Denver, Colorado.

NOMENCLATURE

A	- area for heat flow, sq. ft.
CAP	- capacity, Btu/°R.
C_i	- thermal capacity of node i
C_p	- $\frac{\partial H}{\partial T}$, Btu/lb., °R.
C_T	- $\frac{\partial H}{\partial P}$, Btu/lb., psi.
E	- internal energy, Btu/lb.
E^*	- total fluid energy, Btu.
F_i	- energy input into element i from heat leak or heater current, Btu/min.
H	- enthalpy, Btu/lb.
K	- conductance, Btu/min., °R.
K^*	- radiation conductance, Btu/min., °R.
k	- thermal conductivity, Btu/°R, ft., min.
ℓ	- conductance path length, in.
M_i	- mass in element i, lb.
M_T	- total fluid mass, lb.
$\dot{m}_i$	- mass flow leaving the right side of volume element i, lb./min.
P_m	- mixed pressure, psia.
$\dot{q}$	- heat flow rate, Btu/min.
R	- gas constant, Btu/lb., °R.
r	- radius, in.
T	- temperature, °R.
T_m	- mixed temperature, °R.
t	- time, min.
U	- defined by (19)

V_i - volume of element i, cu. ft.

VOL - volume, cu. ft.

V_T - volume of all fluid elements, cu. ft.

x - distance variable

Z - compressibility factor

Z_P - $\frac{\partial Z}{\partial T}$, $^\circ R^{-1}$.

Z_T - $\frac{\partial Z}{\partial P}$, psi^{-1}.

Δt - time increment, min.

$\mathcal{F}$ - gray body view factor

$\rho_i(P,T_i)$ - fluid density at pressure P and temperature T_i, lb./cu. ft.

σ - Stefan-Boltzmann constant, Btu/min. sq. ft. $^\circ R^4$.

APPENDIX A

STATEMENT OF WORK

SCOPE

An analytical study shall be performed to establish the transient heat and mass transfer characteristics of a supercritical cryogenic storage system in a zero "g" environment. The information which is developed shall include transient temperature profiles in the stored fluid, heater surface temperatures, and vent rates. Only one specific heater design and fluid shall be considered. The results of this effort shall be a generalized computer program for transient three dimensional heat transfer analyses of spherical cryogenic pressurization heaters, which has been checked out with the problems stated herein.

SYSTEM DESCRIPTION

The system shall consist of a spherical vessel with two internal concentric spherical heaters. Fluid shall be withdrawn from the system in accordance with the flow history shown in Figure 1 from a withdrawal port located at the top of the vessel.

The vessel wall shall be considered as the system boundary with a uniform heat leak across the wall of 3.68 Btu per hour. The inside diameter of the vessel shall be 11.14 inches. The two concentric spherical heaters shall have inside diameters of 3.8 inches and 7.6 inches. The heaters are constructed of copper 0.125 inches thick. The heater spheres shall have 50 percent of the surface area removed with lightening holes to

provide for circulation. The holes may be assumed to be equally spaced over the two heaters, and are approximately 0.50 inches in diameter. The heat input from the heaters to the fluid may be assumed to be equal for each unit area of heater surface.

The withdrawal port shall be located at the top of the vessel and shall be 0.50 inches in diameter.

Problem interest shall begin upon completion of vessel filling and continue through the complete cycle of flow demand. The vessel shall be loaded with 26.97 lbm of LOX, at 163°R. and at 14.69 psia. After filling, the system shall be sealed and pressure allowed to rise until an operating pressure of 900 psia is reached. The system shall then enter a vented standby condition until the normal supply portion of the mission is reached. Once operational pressure is reached the system shall operate in a constant pressure mode. The power requirements shall be calculated as a part of this program. All input energy must be assumed to enter the system from the heaters, with the exception of 3.68 Btu per hour which enters through the vessel walls.

The overall system schematic shall be as shown in Figure 2. The gravity profile shall be as shown in Figure 3.

Statement of Work - Delete from the 4th paragraph, Statement of Work, 3.0 System Description, of Reference (b) Operations Directive the sentence which reads: "Once operational pressure is reached the system shall

operate in a constant pressure mode." The following sentence shall be substituted: "Once operational pressure is reached the system shall operate within a range of plus or minus 50 PSI of the operational pressure."

The following sentence shall be added to the above referenced 4th paragraph: "The heater input rate shall be 3600 BTU/HRFT^2 for the actual heater area."

```
$RESTORE
$EXECUTE        IBJOB
$IBJOB          LOGIC,MAP
$IBFTC GULCH    NOLIST,NOREF,M94,XR7
C       TRANSIENT HEAT AND MASS FLOW,NAS9 4444,B.K.LARKIN
C       HEAT LEAK VS. TIME SUBROUTINE
        SUBROUTINE GULCH
        DIMENSION HDATA(16,16),ZDATA(16,16),CDATA(16,16),PR(8),TEM(16),
       1JACK(300),JILL(300),JAN(99),JIM(99),XNDR(99),CAP(99),QIN(99),QS(99
       2),VOL(99),SOURCE(99),CNDR(99),TEMP(99),LOLITA(99),STIR(50)
       3,DENSE(99),THALP(99),FLOW(99),          DOSX(50),ROSA(50)
       4,PUFF(50),SPOT(50)
        COMMON HDATA,ZDATA,CDATA,PR,TEM,T,P,H,CP,CT,Z,C,      PC,RC,RO,
       1JACK,JILL,TEMP,CNDR,CAP,DETEE,SOURCE,NODES,NCNDR,DOSX,ROSA,TIME,
       2ZDOT,PUFF,SPOT,QLEAK,ZT,ZP
         I=2
    12 IF (TIME-PUFF(I)) 10,11,11
    11 I=I+1
        GO TO 12
    10 QLEAK=SPOT(I-1)
        RETURN
        END
$IBFTC SMERSH   NOLIST,NOREF,M94,XR7
C       MASS FLOW VS. TIME SUBROUTINE
        SUBROUTINE SMERSH
        DIMENSION HDATA(16,16),ZDATA(16,16),CDATA(16,16),PR(8),TEM(16),
       1JACK(300),JILL(300),JAN(99),JIM(99),XNDR(99),CAP(99),QIN(99),QS(99
       2),VOL(99),SOURCE(99),CNDR(99),TEMP(99),LOLITA(99),STIR(50)
       3,DENSE(99),THALP(99),FLOW(99),          DOSX(50),ROSA(50)
       4,PUFF(50),SPOT(50)
        COMMON HDATA,ZDATA,CDATA,PR,TEM,T,P,H,CP,CT,Z,C,      PC,RC,RO,
       1JACK,JILL,TEMP,CNDR,CAP,DETEE,SOURCE,NODES,NCNDR,DOSX,ROSA,TIME,
       2ZDOT,PUFF,SPOT,QLEAK,ZT,ZP
        I=2
    12 IF (TIME-DOSX(I)) 10,11,11
    11 I=I+1
```

```
      GO TO 12
   10 ZDOT=ROSA(I-1)
      RETURN
      END
$IBFTC ZOT      NOLIST,NOREF,M94,XR7
C     NEW ZOT
      SUBROUTINE ZOT
      DIMENSION HDATA(16,16),ZDATA(16,16),CDATA(16,16),PR(8),TEM(16),
     1JACK(300),JILL(300),JAN(99),JIM(99),XNDR(99),CAP(99),QIN(99),QS(99
     2),VOL(99),SOURCE(99),CNDR(99),TEMP(99),LOLITA(99),STIR(50)
     3,DENSE(99),THALP(99),FLOW(99),          DOSX(50),ROSA(50)
     4,PUFF(50),SPOT(50)
      COMMON HDATA,ZDATA,CDATA,PR,TEM,T,P,H,CP,CT,Z,C,      PC,RC,RO,
     1JACK,JILL,TEMP,CNDR,CAP,DETEE,SOURCE,NODES,NCNDR,DOSX,ROSA,TIME,
     2ZDOT,PUFF,SPOT,QLEAK,ZT,ZP
      J=1
      DO 1 I=1,NODES
      SUMK=0.
      SUMKT=0.
    4 K=JACK(J)
      IF (K) 2,2,3
    3 SUMK=SUMK+CNDR(K)
      L=JILL(J)
      SUMKT=SUMKT+CNDR(K)*TEMP(L)
      J=J+1
      GO TO 4
    2 U=DETEE*SUMK/CAP(I)
      IF (U-30.) 5,5,6
    6 U=30.
    5 U=EXP(-U)
      TEMP(I)=U*TEMP(I)+(1.-U)*(SUMKT+SOURCE(I))/SUMK
    1 J=J+1
      RETURN
      END
$IBFTC DATA     NOLIST,NOREF,M94,XR7
```

```
      SUBROUTINE DATA
      DIMENSION HDATA(16,16),ZDATA(16,16),CDATA(16,16),PR(8),TEM(16),
     1JACK(300),JILL(300),JAN(99),JIM(99),XNDR(99),CAP(99),QIN(99),QS(99
     2),VOL(99),SOURCE(99),CNDR(99),TEMP(99),LOLITA(99),STIR(50)
     3,DENSE(99),THALP(99),FLOW(99),          DOSX(50),ROSA(50)
     4,PUFF(50),SPOT(50)
      COMMON HDATA,ZDATA,CDATA,PR,TEM,T,P,H,CP,CT,Z,C,      PC,RC,RO,
     1JACK,JILL,TEMP,CNDR,CAP,DETEE,SOURCE,NODES,NCNDR,DOSX,ROSA,TIME,
     2ZDOT,PUFF,SPOT,GLEAK,ZT,ZP
      IF (P-PR(8)) 20,20,21
   21 WRITE (6,25)
      GO TO 27
   20 IF (T-TEM(16)) 22,22,23
   23 WRITE (6,26)
      GO TO 27
   25 FORMAT (28H PRESSURE EXCEEDS DATA TABLE)
   26 FORMAT (31H TEMPERATURE EXCEEDS DATA TABLE)
   22 I=1
    3 IF (PR(I)-P) 1,1,2
    1 I=I+1
      GO TO 3
    2 J=1
    6 IF (TEM(J)-T) 4,4,5
    4 J=J+1
      GO TO 6
    5 DT=TEM(J)-TEM(J-1)
      DP=PR(I)-PR(I-1)
      K=I
      IF (P-PC) 7,8,8
    8 ZILCH=ZDATA(J,I)+ZDATA(J-1,I-1)-ZDATA(J,I-1)-ZDATA(J-1,I)
      ZP=(ZDATA(J,I-1)-ZDATA(J-1,I-1)+(ZILCH*(P-PR(K-1))/DP))/DT
      ZT=(ZDATA(J-1,I)-ZDATA(J-1,I-1))/DP
      Z=ZDATA(J-1,I-1)+ZP*(T-TEM(J-1))+ZT*(P-PR(K-1))
      ZT=ZT+ZILCH*(T-TEM(J-1))/(DP*DT)
      ZILCH=CDATA(J,I)+CDATA(J-1,I-1)-CDATA(J,I-1)-CDATA(J-1,I)
      CP=(CDATA(J,I-1)-CDATA(J-1,I-1)+(ZILCH*(P-PR(K-1))/DP))/DT
```

```
      COT=(CDATA(J-1,I)-CDATA(J-1,I-1))/DP
      C=CDATA(J-1,I-1)+COP*(T-TEM(J-1))+COT*(P-PR(K-1))
      ZILCH=HDATA(J,I)+HDATA(J-1,I-1)-HDATA(J,I-1)-HDATA(J-1,I)
      CP=(HDATA(J,I-1)-HDATA(J-1,I-1)+(ZILCH*(P-PR(K-1))/DP))/DT
      CT=(HDATA(J-1,I)-HDATA(J-1,I-1)+(ZILCH*(T-TEM(J-1))/DT))/DP
      CCT=(HDATA(J-1,I)-HDATA(J-1,I-1))/DP
      H=HDATA(J-1,I-1)+CCT*(P-PR(K-1))+CP*(T-TEM(J-1))
      RB=PR(K-1)/(ZDATA(J-1,I-1)*RC*TEM(J-1))
      R1=PR(K)/(ZDATA(J-1,I)*RC*TEM(J-1))
      R2=PR(K)/(ZDATA(J,I)*RC*TEM(J))
      R3=PR(K-1)/(ZDATA(J,I-1)*RC*TEM(J))
      ZILCH=R2+RB-R1-R3
      F=(T-TEM(J-1))/DT
      RO=RB+(R3-RB)*F+((P-PR(K-1))/DP)*(R1-RB+F*ZILCH)
   24 RETURN
    7 SLOPE=(PR(I)-PR(I-1))/(TEM(I)-TEM(I-1))
      TSTAR=TEM(I-1)+(P-PR(I-1))/SLOPE
      IF (T-TSTAR) 9,9,10
    9 IF (I-J) 11,11,8
   11 CP=(HDATA(J,I)-HDATA(J-1,I))/DT
      CT=(HDATA(J-1,I)-HDATA(J-1,I-1))/DP
      ZP=(ZDATA(J,1)-ZDATA(J-1,I))/DT
      ZT=(ZDATA(J-1,I)-ZDATA(J-1,I-1))/DP
      COP=(CDATA(J,I)-CDATA(J-1,I))/DT
      COT=(CDATA(J-1,I)-CDATA(J-1,I-1))/DP
      RB=PR(I-1)/(ZDATA(J-1,I-1)*RC*TEM(J-1))
      R2=PR(I)/(ZDATA(J,I)*RC*TEM(J))
      R1=PR(I)/(ZDATA(J-1,I)*RC*TEM(J-1))
      RP=(R2-R1)/DT
      RT=(R1-RB)/DP
   13 H=HDATA(J-1,I-1)+CP*(T-TEM(J-1))+CT*(P-PR(K-1))
      Z=ZDATA(J-1,I-1)+ZP*(T-TEM(J-1))+ZT*(P-PR(K-1))
      RO=RB+RP*(T-TEM(J-1))+RT*(P-PR(K-1))
      C=CDATA(J-1,I-1)+COP*(T-TEM(J-1))+COT*(P-PR(K-1))
      RETURN
   10 I=I+6
      IF (J-K) 12,12,8
```

B-4

```
   12 CP=(HDATA(J,I-1)-HDATA(J-1,I-1))/DT
      CT=(HDATA(J,I)-HDATA(J,I-1))/DP
      ZP=(ZDATA(J,I-1)-ZDATA(J-1,I-1))/DT
      ZT=(ZDATA(J,I)-ZDATA(J,I-1))/DP
      COP=(CDATA(J,I-1)-CDATA(J-1,I-1))/DT
      COT=(CDATA(J,I)-CDATA(J,I-1))/DP
      RB=PR(K-1)/(ZDATA(J-1,I-1)*RC*TEM(J-1))
      R1=PR(K-1)/(ZDATA(J,I-1)*RC*TEM(J))
      R2=PR(K)/(ZDATA(J,I)*RC*TEM(J))
      RP=(R1-RB)/DT
      RT=(R2-R1)/DP
      GO TO 13
   27 CALL EXIT
      END
$IBFTC DORF    NOLIST,NOREF,M94,XR7
      DIMENSION HDATA(16,16),ZDATA(16,16),CDATA(16,16),PR(8),TEM(16),
     1JACK(300),JILL(300),JAN(99),JIM(99),XNDR(99),CAP(99),QIN(99),QS(99
     2),VOL(99),SOURCE(99),CNDR(99),TEMP(99),LOLITA(99),STIR(50)
     3,DENSE(99),THALP(99),FLOW(99),          DOSX(50),ROSA(50)
     4,PUFF(50),SPOT(50)
      COMMON HDATA,ZDATA,CDATA,PR,TEM,T,P,H,CP,CT,Z,C,      PC,RC,RO,
     1JACK,JILL,TEMP,CNDR,CAP,DETEE,SOURCE,NODES,NCNDR,DOSX,ROSA,TIME,
     2ZDOT,PUFF,SPOT,QLEAK,ZT,ZP
      DO 688 I=1,10
  688 WRITE (6,105)
      READ (5,101) MWT,QLEAK,VOLUME,ZASS,ZIQMAS,PZERO,PMAX,TTWO
  101 FORMAT (I4,7E10.0)
      IF (MWT-4) 201,202,203
  201 WRITE (6,102)
      L=2
      PC=187.7
      TC=59.4
      GO TO 204
  202 WRITE (6,103)
      L=3
      PC=33.2
```

```
      TC=9.4
      GO TO 204
  203 WRITE (6,104)
      L=1
      PC=734.5
      TC=279.
  204 WRITE (6,105)
      WRITE (6,105)
      WRITE (6,106)
  102 FORMAT (42H ANALYSIS OF SUPERCRITICAL HYDROGEN SYSTEM)
  103 FORMAT (40H ANALYSIS OF SUPERCRITICAL HELIUM SYSTEM)
  104 FORMAT (40H ANALYSIS OF SUPERCRITICAL OXYGEN SYSTEM)
  105 FORMAT ( 1H )
  106 FORMAT( 79H HEAT LEAK VOLUME TOTAL MASS  LIQUID MASS  INITIAL PRES
     1SURE   SUPPLY PRESSURE )
  107 FORMAT(79H  BTU/MIN   CU.FT.     LBS.          LBS.          PSIA
     1              PSIA      )
  108 FORMAT(F8.2,2F10.2,F13.2,F15.2,F18.2)
  109 FORMAT (33H PART I  PRELIMINARY CALCULATIONS)
      WRITE (6,107)
      WRITE (6,105)
      WRITE (6,108) QLEAK,VOLUME,ZASS,ZIQMAS,PZERO,PMAX
      WRITE (6,105)
      WRITE (6,109)
      WRITE (6,105)
      IP=0
C     IRMA IS NUMBER OF SOLID NODES
C     LYDIA IS NUMBER OF GAS  NODES
C     LULU IS NUMBER OF SOLID CONDUCTORS
C     LISA IS NUMBER OF GAS CONDUCTORS
C     KIM IS NUMBER OF RADIATION CONDUCTORS
      READ (5,120) IRMA,LYDIA,LULU,LISA,KIM,DTIME,DTIM,DELP,FLUX
      DETEE=DTIME
      JIP=1
      JUNK=IRMA+1
      LUCY=1
```

```
      LILY=LULU+1
      LOLA=LILY+LISA
      NODES=IRMA+LYDIA
      NCNDR=LOLA+KIM-1
  120 FORMAT (5I4,4E15.5)
  257 READ(5,121) I,J,K,XY,XZ,YZ,LP,NAN
  121 FORMAT (3I4,3E15.5,2I4)
      IF (I-300) 251,252,253
  251 IF (I-201) 254,255,256
  254 JAN(LUCY)=J
      JIM(LUCY)=K
      CNDR(LUCY)=XY
      LUCY=LUCY+1
      GO TO 257
  255 JAN(LILY)=J
      JIM(LILY)=K
      XNDR(LILY)=XY
      LILY=LILY+1
      GO TO 257
  256 JAN(LOLA)=J
      JIM(LOLA)=K
      XNDR(LOLA)=XY
      LOLA=LOLA+1
      GO TO 257
  252 IF (K-1) 258,259,259
  258 CAP(J)=XY
      GIN(J)=XZ
      QS(J)=YZ
      LOLITA(JIP)=J
      JIP=JIP+1
      GO TO 257
  259 VOL(J)=XY
      GIN(J)=XZ
      LOLITA(JUNK)=J
      JUNK=JUNK+1
      GO TO 257
```

```
253 JIP=1
    PEMAX=XY
    SUMF=0.
    SUMV=0.
    IF (NAN) 760,761,761
760 WRITE (6,105)
    WRITE (6,762)
762 FORMAT (40H MASS FLOW BETWEEN FLUID VOLUME ELEMENTS)
    WRITE (6,105)
761 MANCHA=1
    IT=J
    LISP=K
    TIMAX=XZ
    ERP=ZASS
    SUSIE=YZ
    ZAP=0.
    JUNK=IRMA+1
    LOLA=LISA+LULU+1
    LUCY=LULU+LISA
    LILY=LULU+1
    IF (LISP-1) 602,601,601
601 DO 464 I=1,LISP
464 READ (5,160) STIR(I),XY
602 READ (5,689) K
689 FORMAT (I4)
    DO 690 I=1,K
690 READ (5,160) DOSX(I),ROSA(I)
    READ (5,689)  K
    DO 713 I=1,K
713 READ (5,160) PUFF(I),SPOT(I)
160 FORMAT (2E20.5)
    DO 260 K=1,NODES
    DO 261 L=1,NCMBR
    IF (JIM(L)-K)  262,263,262
263 JACK(JIP)=L
    JILL(JIP)=JAN(L)
```

```
      JIP=JIP+1
      GO TO 261
  262 IF (JAN(L)-K) 261,264,261
  264 JACK(JIP)=L
      JILL(JIP)=JIM(L)
      JIP=JIP+1
  261 CONTINUE
      JACK(JIP)=0
      JILL(JIP)=0
      JIP=JIP+1
  260 CONTINUE
      LORA=NODES+2*NCNDR
      CS=0.
      DO 80 I=1,IRMA
      J=LOLITA(I)
   80 CS=CS+CAP(J)
      READ (5,140)
      READ (5,160) (TEM(J),K,L,J=1,16)
      READ (5,140)
      READ (5,100) (PR(J),K,L,J=1,8)
  140 FORMAT ( 80X )
  100 FORMAT (F10.5,I4,62X,I4)
   99 FORMAT (8F9.4,I4,I4)
      READ (5,140)
      READ (5,99) ((HDATA(J,K),K=1,8),N,M,J=1,16)
      READ (5,140)
      READ (5,99) ((HDATA(J,K),K=9,16),N,M,J=1,16)
      READ (5,140)
      READ (5,99) ((ZDATA(J,K),K=1,8),N,M,J=1,16)
      READ (5,140)
      READ (5,99) ((ZDATA(J,K),K=9,16),N,M,J=1,16)
      READ (5,140)
      READ (5,99) ((CDATA(J,K),K=1,8),N,M,J=1,16)
      READ (5,140)
      READ (5,99) ((CDATA(J,K),K=9,16),N,M,J=1,16)
      IF (MMT-M) 194,193,194
```

```
194 WRITE (6,136)
136 FORMAT (38H THERMODYNAMIC DATA INPUT IS INCORRECT)
    GO TO 355
193 XMWT=MWT
    RC=10.71/XMWT
    RS=1.987/XMWT
    I=1
192 IF (PR(I)-PZERO) 190,190,191
190 I=I+1
    GO TO 192
191 SLOPE=(HDATA(I,I)-HDATA(I-1,I-1))/(PR(I)-PR(I-1))
    HL=HDATA(I-1,I-1)+SLOPE*(PZERO-PR(I-1))
    SLOPE=(HDATA(I,I+8)-HDATA(I-1,I+7))/(PR(I)-PR(I-1))
    HV=HDATA(I-1,I+7)+SLOPE*(PZERO-PR(I-1))
    SLOPE=(TEM(I)-TEM(I-1))/(PR(I)-PR(I-1))
    TZERO=TEM(I-1)+SLOPE*(PZERO-PR(I-1))
    HZERO=((ZASS-ZIQMAS)*HV+ZIQMAS*HL)/ZASS
    DO 205 I=1,8
    IF (PC-PR(I)) 205,206,205
206 J=I
205 CONTINUE
    DO 207 K=1,16
    IF (TC-TEM(K)) 207,208,207
208 L=K
207 CONTINUE
    RHOC=PC/(RC*TC*ZDATA(L,J))
    RHO=ZASS/VOLUME
    IF (RHO-RHOC) 209,209,210
209 I=9
214 K=I-8
    RHOT=PR(K)/(RC*TEM(K)*ZDATA(K,I))
    IF (RHOT-RHO) 213,691,691
213 I=I+1
    GO TO 214
210 I=1
217 RHOT=PR(I)/(RC*TEM(I)*ZDATA(I,I))
```

```
      IF (RHOT-RHO) 215,215,216
  216 I=I+1
      GO TO 217
  215 K=I
  691 FR=PR(K-1)/(RC*TEM(K-1)*ZDATA(K-1,I-1))
      SLOPE=(HDATA(K,I)-HDATA(K-1,I-1))/(RHOT-FR)
      HTWO=HDATA(K-1,I-1)+SLOPE*(RHO-FR)
      SLOPE=(PR(K)-PR(K-1))/(RHOT-FR)
      PTWO=PR(K-1)+SLOPE*(RHO-FR)
      SLOPE=(TEM(K)-TEM(K-1))/(RHOT-FR)
      TONE=TEM(K-1)+SLOPE*(RHO-FR)
      ST=((HTWO-HZERO)*ZASS-VOLUME*(PTWO-PZERO)*.185+CS*(TONE-TZERO))/QL
     1EAK
      IF (PZERO-PTWO) 700,700,701
  701 P=PZERO
      T=TEM(1)
  704 CALL DATA
      IF (RO-RHO) 702,702,703
  703 T=T+1.
      ROLD=RO
      GO TO 704
  702 SLOPE=RO-ROLD
      T=T-1.+(RHO-ROLD)/SLOPE
      TZERO=T
      CALL DATA
      TONE=T
      PTWO=PZERO
      ST=0.
      HZERO=H
  700 WRITE (6,110)
  110 FORMAT(78H STANDBY TIME,MINS          STARTING PRESSURE,PSIA
     1  STARTING TEMP. DEG.R)
      WRITE (6,111) ST, PTWO,TONE
  111 FORMAT (F14.3,13X,F15.1,15X,F15.2)
      WRITE (6,105)
  112 FORMAT (28H NO VENTING IS NECESSARY,ADD,F12.4, 4H BTU)
```

```
113 FORMAT ( 8H VENT AT,F12.4,8H MINUTES)
    P=PEMAX
    I=1
224 T=TEM(I)
    CALL DATA
    RHOT=P/(Z*RC*T)
    IF(RHOT-RHO)  226,226,225
225 I=I+1
    FR=RHOT
    GO TO 224
226 SLOPE=(TEM(I)-TEM(I-1))/(RHOT-FR)
    T=TEM(I-1)+SLOPE*(RHO-FR)
    CALL DATA
    DT=(ZASS*(H-HZERO)-VOLUME*(PEMAX-PZERO)*.185+CS*(T-TZERO))/QLEAK
    IF (DT-TTWO) 221,222,222
222 Q=(DT-TTWO)*QLEAK
    WRITE (6,112) Q
    QDOT=Q/(TTWO-ST)
    GO TO 223
221 WRITE (6,113) DT
    QDOT=0.
223 P=PTWO
    TIME=ST
    IF (SUSIE) 83,82,82
 82 DO 270 I=1,NODES
    T=TONE
    CALL DATA
    DENSE(I)=RO
    SOURCE(I)=0.
270 TEMP(I)=TONE
    GO TO 503
450 ZSAZSA=0.
    J=1
    DO 454 I=1,NODES
    SUM=0.
456 K=JACK(J)
```

```
      IF (K) 457,457,455
  455 SUM=SUM+DETEE*CNDR(K)/CAP(I)
      J=J+1
      GO TO 456
  457 J=J+1
      IF (SUM-ZSAZSA) 454,454,458
  458 ZSAZSA=SUM
      MANDY=I
  454 CONTINUE
      WRITE (6,105)
      WRITE (6,131) ZSAZSA,MANDY
      WRITE (6,105)
  131 FORMAT (27H     MAXIMUM OF DT*SUMK/CAP,F15.2,I4)
      GO TO (500,501,502),MABEL
  503 DPDT=0.
C     BEGIN PRESSURE RISE CALCULATION
  272 IF (NAN) 730,731,731
  731 DO 271 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
      CAP(J)=VOL(J)*RO*CP
  271 QS(J)=VOL(J)*DPDT*(.185-CT*RO)
      DO 275 I=1,NODES
      CALL GULCH
      J=LOLITA(I)
      IF (I-IRMA) 276,276,277
  276 SOURCE(J)=QS(J)*QDOT+QIN(J)*QLEAK
      GO TO 275
  277 SOURCE(J)=QS(J)+QIN(J)*QLEAK
  275 CONTINUE
      GO TO 732
  730 DO 733 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
```

```
733 CAP(J)=VOL(J)*RO*(CP-RS*Z-RS*T*ZP)
    CALL GULCH
    SUM=0.
    DO 734 I=1,LYDIA
    T=TEMP(I)
    CALL DATA
    FLOW(I)=SUM+VOL(I)*(DENSE(I)-RO)/DETEE
    SUM=FLOW(I)
    DENSE(I)=RO
734 THALP(I)=H
    DO 735 I=1,LYDIA
    T=TEMP(I)
    CALL DATA
    IF (I-1) 736,736,737
736 SOURCE(I)=-FLOW(I)*Z*RS*T-VOL(I)*RO*DPDT*(CT-RS*T*ZT)+QIN(I)*QLEAK
    GO TO 735
737 SOURCE(I)=FLOW(I-1)*(THALP(I-1)-H+Z*RS*T)-FLOW(I)*Z*RS*T-VOL(I)*
   1RO*(CT-RS*T*ZT)*DPDT+QIN(I)*QLEAK
735 CONTINUE
    DO 738 I=1,IKMA
    J=LOLITA(I)
738 SOURCE(J)=QS(J)*QDOT+QIN(J)*QLEAK
732 IF (LOLA-NCNDR) 607,607,608
607 DO 273 I=LOLA,NCNDR
    J=JAN(I)
    K=JIM(I)
273 CNDR(I)=XNDR(I)*(TEMP(J)+TEMP(K))*(TEMP(J)**2+TEMP(K)**2)
608 DO 274 I=LILY,LUCY
    J=JAN(I)
    K=JIM(I)
    T=(TEMP(J)+TEMP(K))/2.
    CALL DATA
274 CNDR(I)=XNDR(I)*C
    CALL ZOT
    POLD=P
    SUM=0.
```

```
      DO 650 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
  650 SUM=SUM+RO*VOL(J)
      IF (SUM-ZASS) 651,651,652
  652 SOLD=SUM
      P=P-1.
      SUM=0.
      DO 653 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
  653 SUM=SUM+VOL(J)*RO
      IF (SUM-ZASS) 654,654,652
  654 SLOPE=1./(SOLD-SUM)
      P=P+SLOPE*(ZASS-SUM)
      GO TO 655
  651 SOLD=SUM
      P=P+1.
      SUM=0.
      DO 657 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
  657 SUM=SUM+VOL(J)*RO
      IF (SUM-ZASS) 651,656,656
  656 SLOPE=1./(SUM-SOLD)
      P=P-SLOPE*(SUM-ZASS)
  655 DPDT=(P-POLD)/DETEE
  717 TIME=TIME+DETEE
      IF (TIME-TIMAX) 510,355,355
  510 IF (P-PEMAX) 295,296,296
  295 IP=IP+1
      IF (IP-IT) 272,297,297
  297 IP=0
```

```
      WRITE (6,105)
      WRITE (6,114) TIME,P
      WRITE (6,105)
  114 FORMAT ( 5H TIME,F15.1,18H MIN.     PRESSURE,F15.1,5H PSIA)
      MABEL=1
      GO TO 450
  500 WRITE (6,115)
  115 FORMAT (7H NODE  ,20H TEMPERATURE,DEG. R.,20H TEMPERATURE,DEG. F.)
      WRITE (6,105)
      DO 298 I=1,NODES
      SUM=TEMP(I)-459.6
  298 WRITE (6,116) I,TEMP(I),SUM
      WRITE (6,105)
      GO TO 272
  116 FORMAT (I4,F14.2,7XF14.2)
  296 P=PEMAX
      DPDT=0.
      WRITE (6,117) PEMAX,TIME
  117 FORMAT(14H MAX.PRESSURE,,F10.1, 8H PSIA AT,F15.2, 5H MIN.)
      IP=0
      IF (TIME-TIWO) 303,323,323
C     BEGIN VENTING CALCULATION
  303 IF (NAN) 740,741,741
  741 DO 300 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
  300 CAP(J)=VOL(J)*CP*RO
      CALL GULCH
      DO 304 I=1,NODES
  304 SOURCE(I)=QIN(I)*GLEAK
      GO TO 739
  740 DO 742 I=1,LYDIA
      J=1+LYDIA-I
      I=TEMP(J)
      CALL DATA
```

```
      CAP(J)=VOL(J)*RO*(CP-RS*Z-RS*T*ZP)
      THALP(J)=H
      FLOW(J)=ZAP
      ZAP=ZAP+(RO-DENSE(J))*VOL(J)/DETEE
  742 DENSE(J)=RO
      CALL GULCH
      DO 743 I=1,IRMA
      J=LOLITA(I)
  743 SOURCE(J)=QIN(J)*QLEAK
      DO 744 I=1,LYDIA
      T=TEMP(I)
      CALL DATA
      IF (I-1) 745,745,746
  745 SOURCE(1)=QIN(1)*QLEAK-FLOW(1)*Z*RS*T
      GO TO 744
  746 SOURCE(I)=QIN(I)*QLEAK+FLOW(I-1)*(THALP(I-1)-H+Z*RS*T)-FLOW(I)*Z*
     1RS*T
  744 CONTINUE
  739 IF (LOLA-NCNDR) 611,611,612
  611 DO 301 I=LOLA,NCNDR
      J=JAN(I)
      K=JIM(I)
  301 CNDR(I)=XNDR(I)*(TEMP(J)+TEMP(K))*(TEMP(J)**2+TEMP(K)**2)
  612 DO 302 I=LILY,LUCY
      J=JAN(I)
      K=JIM(I)
      T=(TEMP(J)+TEMP(K))/2.
      CALL DATA
  302 CNDR(I)=XNDR(I)*C
      CALL ZOT
      DM=0.
      DO 321 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
  321 DM=DM+VOL(J)*RO
```

```
      ZAP=(ZASS-DM)/DETEE
      ZASS=DM
      TIME=TIME+DETEE
      IF (ZASS-.05*ERP) 355,355,513
  513 IF (TIME-TIMAX) 511,355,355
  511 IF (TIME-TTWO) 322,323,323
  322 IP=IP+1
      IF (IP-IT) 303,324,324
  324 IP=0
      WRITE (6,105)
      WRITE (6,118) TIME,P,ZASS
  118 FORMAT ( 5H TIME,F15.1,18H MIN.      PRESSURE,F15.1,16H PSIA
     1MASS,F15.3,19H   LBS.      VENTING)
      WRITE (6,105)
      MODEL=2
      GO TO 450
  501 WRITE (6,115)
      WRITE (6,105)
      DO 325 I=1,NODES
      SUM=TEMP(I)-459.6
  325 WRITE (6,116) I,TEMP(I),SUM
      WRITE (6,105)
      GO TO 303
C     BEGIN OF FLUID WITHDRAWAL CALCULATION
  323 IP=0
      WRITE (6,119) TIME
  119 FORMAT(26H      FLUID WITHDRAWAL TIME,F15.1, 6H MINS.)
      POLD=P
  350 DPDT=(P-POLD)/DETEE
      IF (NAN) 750,751,751
  751 DO 328 I=JUNK,NODES
      J=LOLITA(I)
      T=TEMP(J)
      CALL DATA
      QS(J)=DPDT*VOL(J)*(.185-RO*CT)
  328 CAP(J)=VOL(J)*CP*RO
```

```
      CALL GULCH
      DO 332 I=1,NODES
      J=LOLITA(I)
      IF (I-IRMA) 326,326,327
  327 SOURCE(J)=QS(J)+QIN(J)*QLEAK
      GO TO 332
  326 SOURCE(J)=QS(J)*QDOT+QIN(J)*QLEAK
  332 CONTINUE
      GO TO 752
  750 DO 753 I=1,LYDIA
      J=1+LYDIA-I
      T=TEMP(J)
      CALL DATA
      CAP(J)=VOL(J)*RO*(CP-RS*Z-RS*T*ZP)
      THALP(J)=H
      FLOW(J)=ZAP
      ZAP=ZAP+(RO-DENSE(J))*VOL(J)/DETEE
  753 DENSE(J)=RO
      CALL GULCH
      DO 754 I=1,IRMA
      J=LOLITA(I)
  754 SOURCE(J)=QIN(J)*QLEAK+QS(J)*QDOT
      DO 755 I=1,LYDIA
      T=TEMP(I)
      CALL DATA
      IF (I-1) 756,756,757
  756 SOURCE(I)=QIN(I)*QLEAK-FLOW(I)*Z*RS*T-VOL(I)*RO*(CT-ZT*RS*T)*DPDT
      GO TO 755
  757 SOURCE(I)=FLOW(I-1)*(THALP(I-1)-H+Z*RS*T)-FLOW(I)*Z*RS*T-QIN(I)*
     1QLEAK-VOL(I)*RO*DPDT*(CT-ZT*RS*T)
  755 CONTINUE
  752 IF (LOLA-NCNDR) 613,613,614
  613 DO 329 I=LOLA,NCNDR
      J=JAN(I)
      K=JIM(I)
  329 CNDR(I)=XNDR(I)*(TEMP(J)+TEMP(K))*(TEMP(J)**2+TEMP(K)**2)
```

```
614 DO 330 I=LILY,LUCY
    J=JAN(I)
    K=JIM(I)
    T=(TEMP(J)+TEMP(K))/2.
    CALL DATA
330 CNDR(I)=XNDR(I)+C
    CALL ZOT
    CALL SMERSH
    ZASS=ZASS-DETEE+ZDOT
    POLD=P
    SUM=0.
    DO 347 I=JUNK,NODES
    J=LOLITA(I)
    T=TEMP(J)
    CALL DATA
347 SUM=SUM+VOL(J)*RO
    IF (SUM-ZASS) 660,660,661
661 SOLD=SUM
    P=P-1.
    SUM=0.
    DO 662 I=JUNK,NODES
    J=LOLITA(I)
    T=TEMP(J)
    CALL DATA
662 SUM=SUM+VOL(J)*RO
    IF (SUM-ZASS) 663,663,661
663 SLOPE=1./(SOLD-SUM)
    P=P+SLOPE*(ZASS-SUM)
    GO TO 664
660 SOLD=SUM
    P=P+1.
    SUM=0.
    DO 665 I=JUNK,NODES
    J=LOLITA(I)
    T=TEMP(J)
    CALL DATA
```

```
665 SUM=SUM+VOL(J)*RO
    IF (SUM-ZASS) 660,666,666
666 SLOPE=1./(SUM-SOLD)
    P=P-SLOPE*(SUM-ZASS)
664 TIME=TIME+DETEE
    ZAP=ZDOT
    IF (P-PEMAX) 697,697,698
698 P=PEMAX
    SUM=0.
    DO 699 I=JUNK,NODES
    J=LOLITA(I)
    T=TEMP(J)
    CALL DATA
699 SUM=SUM+VOL(J)*RO
    VENT=ZASS-SUM
    ZAP=ZDOT+VENT/DETEE
    SUMV=SUMV+VENT
    ZASS=SUM
697 SUMF=SUMF+QDOT*DETEE
    IF (P-PMAX-DELP) 348,348,349
349 QDOT=0.
    DETEE=DTIME
348 IF (PMAX-DELP-P) 156,156,351
351 QDOT=FLUX
    DETEE=DTIM
156 IP=IP+1
352 IF(LISP) 360,360,460
460 IF (TIME-STIR(MANCHA)) 360,398,398
360 IF (TIME-TIMAX)354,355,355
354 IF (ZASS-.05*ERP) 355,355,356
356 IF (IP-LP) 350,357,357
357 IP=0
    WRITE (6,105)
    WRITE (6,105)
    WRITE (6,122)
122 FORMAT(114H    TIME,MINUTES     PRESSURE,PSIA     STORED MASS,LBS
```

```
     1    HEAT FLUX,BTU/MIN     HEAT INPUT,BTU     EXCESS VENT,LB)
          WRITE (6,105)
          WRITE (6,123) TIME,P,ZASS,GDOT,SUMF,SUMV
   123 FORMAT (F11.1,F19.1,F19.3,F24.5,F15.3,F15.3)
          WRITE (6,105)
          MABEL=5
          GO TO 450
   502 WRITE (6,115)
          WRITE (6,105)
          DO 358 I=1,NODES
          SUM=TEMP(I)-459.6
   358 WRITE (6,116) I,TEMP(I),SUM
          GO TO 350
C         SUBROUTINE MIXUP
   398 TP=TEMP(I)
          MANCHA=MANCHA+1
          DO 400 I=1,NODES
          IF (TEMP(I)-TP) 402,400,400
   402 TP=TEMP(I)
   400 CONTINUE
          EONE=0.
          DO 399 I=JUNK,NODES
          J=LOLITA(I)
          T=TEMP(J)
          CALL DATA
   399 EONE=EONE+VOL(J)*RO*(H-Z*.185*RC*T)
          LINDA=1
          PSAVE=P
   401 SUM=0.
          T=TP
          CALL DATA
          DO 680 I=JUNK,NODES
          J=LOLITA(I)
   680 SUM=SUM+VOL(J)*RO
          IF (SUM-ZASS) 681,681,682
   682 SOLO=SUM
```

```
      P=P-2.
      CALL DATA
      SUM=0.
      DO 683 I=JUNK,NODES
      J=LOLITA(I)
  683 SUM=SUM+VOL(J)*RO
      IF (SUM-ZASS) 684,684,682
  684 SLOPE=2./(SOLD-SUM)
      P=P+SLOPE*(ZASS-SUM)
      GO TO 685
  681 SOLD=SUM
      P=P+2.
      CALL DATA
      SUM=0.
      DO 686 I=JUNK,NODES
      J=LOLITA(I)
  686 SUM=SUM+VOL(J)*RO
      IF (SUM-ZASS) 681,687,687
  687 SLOPE=2./(SUM-SOLD)
      P=P-SLOPE*(SUM-ZASS)
  685 IF (LINDA-1) 406,406,407
  406 CALL DATA
      F=EONE-ZASS*(H-.185*Z*RC*TP)
      IF (F) 410,410,409
  409 TP=TP+5.
      FOLD=F
      GO TO 401
  410 LINDA=2
      SLOPE=(F-FOLD)/5.
      TP=TP-5.-FOLD/SLOPE
      GO TO 401
  407 WRITE (6,105)
      WRITE (6,125)
      WRITE (6,105)
      WRITE (6,126) P,TP,TIME
      IF (SUSIE) 462,462,463
```

```
462 P=PSAVE
    GO TO 360
463 DO 331 I=JUNK,NODES
    J=LOLITA(I)
331 TEMP(J)=TP
    GO TO 360
125 FORMAT(65H MIXED PRESSURE,PSIA      MIXED TEMPERATURE,DEG. R.
   1TIME,MIN.)
126 FORMAT(F13.2,F26.1,F23.1)
 83 WRITE (6,105)
    WRITE (6,127)
    WRITE (6,105)
127 FORMAT (29H      COMPLETE MIXING OPTION  )
    P=PEMAX
    IF (DT-TTWO) 411,412,412
411 TIME=DT
    WRITE (6,128) TIME,P,T,ZASS
128 FORMAT(6H TIME,F10.1,18H MIN.      PRESSURE,F10.1,21H PSIA      TEM
   1PERATURE,F10.1,17H DEG. R.      MASS,F10.3,17H LBS.      VENTING)
    CALL DATA
413 CALL GULCH
    DELT=(QLEAK*DETEE)/(ZASS*CP+CS)
    T=T+DELT
    CALL DATA
    ZASS=VOLUME*RO
    IP=IP+1
    TIME=TIME+DETEE
    IF (TIME-TIMAX) 512,355,355
512 IF (TIME-TTWO) 414,412,412
414 IF (IP-IT) 413,415,415
415 WRITE (6,105)
    IP=0
    WRITE (6,128) TIME,P,T,ZASS
    GO TO 413
412 TIME=TTWO
    WRITE (6,105)
```

```
      WRITE (6,119) TIME
      WRITE (6,105)
      DELT=2.
      WRITE (6,130)
      WRITE (6,141)
  130 FORMAT(120H TIME,MINUTES     PRESSURE,PSIA     TEMPERATURE,DEG.R.
     1 STORED MASS,LBS.     HEAT FLUX,BTU/MIN     HEAT INPUT,BTU    EXCESS)
  141 FORMAT(120H
     1                                                              VENT  )
  416 EMZERO=ZASS
      T=T+DELT
      CALL DATA
      ZASS=VOLUME*RO
      CALL SMERSH
      DETEE=(EMZERO-ZASS)/ZDOT
      CALL GULCH
      QDOT=(EMZERO*CP+CS)*DELT/DETEE-QLEAK
      IF (QDOT) 695,695,696
  695 QDOT=0.
      DETEE=(EMZERO*CP+CS)*DELT/QLEAK
      VENT=EMZERO-ZASS-ZDOT*DETEE
      SUMV=SUMV+VENT
  696 SUMF=SUMF+QDOT*DETEE
      TIME=TIME+DETEE
      IP=IP+1
      IF (TIME-TIMAX) 417,417,355
  417 IF (ZASS-.05*ERP) 355,418,418
  418 IF (IP-LP) 416,419,419
  419 WRITE (6,105)
      IP=0
      WRITE (6,129) TIME,P,T,ZASS,QDOT,SUMF,SUMV
  129 FORMAT (2F14.1,F21.1,F24.2,F24.5,2F10.3)
      GO TO 416
  355 CALL EXIT
      STOP
      END
```

```
R
  32   0.061     0.418      26.97      26.97      14.7      900.0     11460.0
   3     6     0  10   2          1.                .5          50.           2.
 201     1     2     0.381              0.0              0.0
 201     2     7     6.021              0.0              0.0
 201     2     3     4.105              0.0              0.0
 201     7     3     10.671             0.0              0.0
 201     3     4     9.6                0.0              0.0
 201     4     8     25.143             0.0              0.0
 201     8     5     39.518             0.0              0.0
 201     4     5     15.947             0.0              0.0
 201     5     6     28.335             0.0              0.0
 201     6     9     67.638             0.0              0.0
 202     7     8     8.99    E-12       0.0              0.0
 202     8     9     3.60    E-11       0.0              0.0
 300     1     1     0.002              0.0              0.0
 300     2     1     0.015              0.0              0.0
 300     3     1     0.038              0.0              0.0
 300     4     1     0.077              0.0              0.0
 300     5     1     0.116              0.0              0.0
 300     6     1     0.170              0.0              0.0
 300     7     0     .0162              0.0              0.2025
 300     8     0     .0648              0.0              0.7975
 300     9     0     .4780              1.0              .0
 301    60     7          1000.         15000.     -1.0                2    1
  11500.
  12000.
  12500.
  13000.
  13500.
  14000.
  15000.
   3
  11460.                  .01037
  13000.                  .02
  25000.                  .01037
```

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```
3
.0                    .061
11460.                .061
25000.                .061
OXYGEN TEMPERATURE VECTOR (DEG. R.)
 162.      1                                                          32
 191.      2                                                          32
 205.      3                                                          32
 216.      4                                                          32
 268.      5                                                          32
 279.      6                                                          32
 360.      7                                                          32
 450.      8                                                          32
 540.      9                                                          32
 630.     10                                                          32
 720.     11                                                          32
 900.     12                                                          32
1080.     13                                                          32
1260.     14                                                          32
1440.     15                                                          32
1620.     16                                                          32
OXYGEN PRESSURE VECTOR (PSIA)
  14.69    1                                                          32
  58.76    2                                                          32
 102.8     3                                                          32
 146.9     4                                                          32
 587.6     5                                                          32
 734.5     6                                                          32
1026.      7                                                          32
1469.      8                                                          32
OXYGEN LIQUID AND SUPERCRITICAL ENTHALPY DATA (BTU/LB)
 60.54   60.47   60.53   60.60   61.30   61.54   62.01   62.73   1   32
         72.64   72.77   72.82   73.36   73.55   73.93   74.53   2   32
                 79.12   79.15   79.55   79.70   80.01   80.52   3   32
                         83.89   84.24   84.35   84.59   85.00   4   32
                                 112.8   110.8   109.0   107.8   5   32
                                                                     *
```

				158.8	133.1	116.1	113.4	6	32
				186.7	185.4	178.4	169.3	7	32
				209.9	209.1	205.3	200.8	8	32
				231.4	230.9	228.4	225.5	9	32
				252.2	251.5	249.9	247.8	10	32
				273.1	272.5	271.5	269.9	11	32
				315.3	315.0	314.4	313.6	12	32
				358.4	358.3	358.0	357.6	13	32
				402.6	402.5	402.5	402.5	14	32
				447.8	447.8	447.9	448.1	15	32
				493.7	493.7	494.1	494.5	16	32

OXYGEN VAPOR AND SUPERCRITICAL ENTHALPY DATA (BTU/LB)

152.5								1	32
158.8	156.7							2	32
162.0	160.1	158.0						3	32
164.5	162.7	160.8	158.6					4	32
176.0	174.8	173.6	172.4	151.3				5	32
178.3	177.3	176.1	175.0	158.8	133.1	116.1	113.4	6	32
196.1	195.4	194.7	194.0	186.7	185.4	178.4	169.3	7	32
215.7	215.3	214.9	214.4	209.9	209.1	205.3	200.8	8	32
235.5	235.1	234.8	234.5	231.4	230.9	228.4	225.5	9	32
255.3	255.1	254.8	254.6	252.2	251.5	249.9	247.8	10	32
275.4	275.2	275.1	274.9	273.1	272.5	271.5	269.9	11	32
316.5	316.4	316.3	316.2	315.3	315.0	314.4	313.6	12	32
359.0	358.9	358.9	358.8	358.4	358.3	358.0	357.6	13	32
402.7	402.7	402.7	402.7	402.6	402.5	402.5	402.5	14	32
447.6	447.6	447.6	447.6	447.8	447.8	447.9	448.1	15	32
493.3	493.3	493.4	493.4	493.7	493.7	494.1	494.5	16	32

OXYGEN LIQUID AND SUPERCRITICAL COMPRESSIBILITY DATA

.00380	.01518	.02054	.03790	.1587	.1881	.2623	.3729	1	32
	.01393	.02436	.03477	.1378	.1717	.2390	.3388	2	32
		.02380	.03395	.1341	.1670	.2320	.3282	3	32
			.03352	.1320	.1642	.2277	.3214	4	32
				.1511	.1785	.2352	.3189	5	32
				.6440	.2895	.2511	.3275	6	32
				.8768	.8450	.7819	.6981	7	32

*

				•9490	•9378	•9144	•8865	8	32
				•9791	•9750	•9671	•9577	9	32
				•9900	•9900	•9900	•9890	10	32
				1.0	1.0	1.0	1.01	11	32
				1.01	1.01	1.02	1.03	12	32
				1.01	1.01	1.02	1.03	13	32
				1.01	1.01	1.02	1.03	14	32
				1.01	1.01	1.02	1.03	15	32
				1.01	1.01	1.02	1.03	16	32

OXYGEN VAPOR AND SUPERCRITICAL COMPRESSIBILITY DATA

•9692									
•9861	•9119							1	32
•9847	•9321	•8724						2	32
•9845	•9411	•8914	•8352					3	32
•9906	•9700	•9461	•9219	•5363				4	32
•9937	•9737	•9521	•9307	•6440	•2895	•2511	•3275	5	32
•9974	•9872	•9787	•9703	•8768	•8450	•7819	•6981	6	32
•9984	•9958	•9901	•9872	•9490	•9378	•9144	•8865	7	32
•9990	•9984	•9959	•9941	•9791	•9750	•9671	•9577	8	32
1.0000	1.0000	1.0000	1.0000	•9900	•9900	•9900	•9890	9	32
1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0100	10	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	11	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	12	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	13	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	14	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	15	32
1.0000	1.0000	1.0000	1.0000	1.0100	1.0100	1.0200	1.0300	16	32

OXYGEN LIQUID AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)

•0016187	•0016187	•0016187	•0016187	•0016187	•0016194	•0016258	•0016410	1	32
	•0012396	•0012406	•0012425	•0012531	•0012627	•0012767	•0012897	2	32
		•0011365	•0011385	•0011539	•0011653	•0011825	•0011996	3	32
			•0007345	•0010801	•0010917	•0011105	•0011293	4	32
				•0006439	•0006550	•0006861	•0007436	5	32
				•0002137	•0003883	•0005871	•0006609	6	32
				•0002100	•0002241	•0002569	•0003254	7	32
				•0002400	•0002475	•0002660	•0002975	8	32
				•0002754	•0002813	•0002942	•0003160	9	32
				•0003120	•0003185	•0003290	•0003410	10	32

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                                        .0003500 .0003560 .0003640 .0003760  11  32
                                        .0004185 .0004245 .0004325 .0004450  12  32
                                        .0004810 .0004870 .0004960 .0005096  13  32
                                        .0005448 .0005508 .0005590 .0005725  14  32
                                        .0006081 .0006146 .0006220 .0006355  15  32
                                        .0006724 .0006784 .0006850 .0006985  16  32
OXYGEN VAPOR AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)
 .0000779                                                                    1  32
 .0000923 .0000973                                                           2  32
 .0000990 .0001040 .0001078                                                  3  32
 .0001050 .0001100 .0001138 .0001175                                         4  32
 .0001309 .0001359 .0001397 .0001434 .0002231                                5  32
 .0001363 .0001408 .0001443 .0001477 .0002137 .0003883 .0005871 .0006609     6  32
 .0001757 .0001784 .0001804 .0001824 .0002100 .0002241 .0002569 .0003254     7  32
 .0002133 .0002161 .0002163 .0002205 .0002400 .0002475 .0002660 .0002976     8  32
 .0002577 .0002593 .0002603 .0002615 .0002754 .0002813 .0002942 .0003160     9  32
 .0002957 .0002970 .0002980 .0002992 .0003120 .0003185 .0003290 .0003410    10  32
 .0003335 .0003347 .0003357 .0003370 .0003500 .0003560 .0003640 .0003760    11  32
 .0004020 .0004032 .0004042 .0004055 .0004185 .0004245 .0004325 .0004450    12  32
 .0004658 .0004670 .0004680 .0004693 .0004810 .0004870 .0004960 .0005095    13  32
 .0005296 .0005308 .0005318 .0005331 .0005448 .0005508 .0005590 .0005725    14  32
 .0005934 .0005946 .0005956 .0005969 .0006086 .0006146 .0006220 .0006355    15  32
 .0006572 .0006584 .0006594 .0006607 .0006724 .0006784 .0006850 .0006985    16  32
R
$IBSYS
$TIME
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HELIUM TEMPERATURE VECTOR (DEG. R.)

7.6	1	4
9.1	2	4
9.4	3	4
54.0	4	4
108.0	5	4
180.0	6	4
270.0	7	4
360.0	8	4
450.0	9	4
540.0	10	4
630.0	11	4
720.0	12	4
810.0	13	4
900.0	14	4
990.0	15	4
1080.0	16	4

HELIUM PRESSURE VECTOR (PSIA)

14.69	1	4
29.38	2	4
33.20	3	4
146.90	4	4
587.60	5	4
1469.0	6	4
2056.6	7	4
3084.9	8	4

HELIUM LIQUID AND SUPERCRITICAL ENTHALPY DATA (BTU/LB)

4.291	4.580	4.626	5.994	12.745	25.237	31.10	38.80	1	4
	7.086	7.087	7.129	13.545	25.908	31.60	39.10	2	4
		9.900	7.529	13.799	26.105	31.70	39.20	3	4
		72.981	72.124	71.260	71.900	73.2	76.3	4	4
		140.31	140.50	141.98	143.00	145.7	150.8	5	4
		229.76	230.40	233.15	239.36	240.1	247.4	6	4
		341.47	342.34	345.84	353.10	354.9	363.7	7	4
		453.14	454.14	458.04	465.96	467.9	477.4	8	4
		564.80	565.87	570.03	578.38	580.4	590.0	9	4

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		676.45	677.57	681.91	690.58	692.2	702.1	10	4
		784.44	785.57	789.78	798.30	802.5	812.5	11	4
		896.14	897.27	901.48	910.00	927.1	937.7	12	4
		1007.94	1008.97	1012.98	1021.70	1033.2	1037.5	13	4
		1119.63	1120.57	1124.48	1133.30	1140.1	1141.2	14	4
		1231.23	1232.17	1236.18	1244.90	1251.7	1252.8	15	4
		1348.03	1348.93	1352.70	1362.00	1368.0	1369.6	16	4

HELIUM VAPOR AND SUPERCRITICAL ENTHALPY DATA (BTU/LB)

13.278								1	4
15.583	11.902							2	4
16.237	11.963	9.900	7.529	13.799	26.105	31.70	39.20	3	4
73.147	73.010	72.981	72.124	71.260	71.900	73.2	76.3	4	4
140.29	140.30	140.31	140.50	141.98	143.00	145.7	150.8	5	4
229.66	229.74	229.76	230.40	233.15	239.36	240.1	247.4	6	4
341.33	341.44	341.47	342.34	345.84	353.10	354.9	363.7	7	4
452.98	453.11	453.14	454.14	458.04	465.96	467.9	477.4	8	4
564.62	564.76	564.80	565.87	570.03	578.38	580.4	590.0	9	4
676.27	676.41	676.45	677.57	681.91	690.58	692.2	702.1	10	4
784.30	784.40	784.44	785.57	789.78	798.30	802.5	812.5	11	4
895.90	896.10	896.14	897.27	901.48	910.00	927.1	937.7	12	4
1007.8	1007.90	1007.94	1008.97	1012.98	1021.70	1033.2	1037.5	13	4
1119.6	1119.60	1119.63	1120.57	1124.48	1133.30	1140.1	1141.2	14	4
1231.2	1231.20	1231.23	1232.17	1236.18	1244.90	1251.7	1252.8	15	4
1348.0	1348.00	1348.03	1348.93	1352.70	1362.00	1368.0	1369.6	16	4

HELIUM LIQUID AND SUPERCRITICAL COMPRESSIBILITY DATA

.09269	.17513	.19694	.76688	2.5281	5.4418	7.2137	10.2850	1	4
	.19677	.21907	.67335	2.1576	4.5880	6.0419	8.6189	2	4
		.27105	.66334	2.1163	4.5304	5.9642	8.3495	3	4
		1.0036	1.0199	1.1558	1.4978	1.7002	2.0893	4	4
		1.0052	1.0205	1.0867	1.2301	1.3243	1.4964	5	4
		1.0042	1.0147	1.0568	1.1410	1.1964	1.2888	6	4
		1.0031	1.0107	1.0401	1.0967	1.1346	1.1958	7	4
		1.0026	1.0085	1.0294	1.0848	1.1070	1.1542	8	4
		1.0017	1.0064	1.0313	1.0615	1.0826	1.1402	9	4
		1.0015	1.0052	1.0222	1.0518	1.0712	1.1071	10	4
		1.0015	1.0047	1.0184	1.0449	1.0620	1.0917	11	4
		1.0013	1.0043	1.0165	1.0399	1.0550	1.0807	12	4
		1.0013	1.0040	1.0147	1.0358	1.0494	1.0726	13	4
		1.0013	1.0037	1.0134	1.0323	1.0449	1.0658	14	4
		1.0013	1.0035	1.0124	1.0296	1.0411	1.0599	15	4
		1.0012	1.0034	1.0114	1.0270	1.0370	1.0556	16	4

HELIUM VAPOR AND SUPERCRITICAL COMPRESSIBILITY DATA

.69235								1	4

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.80831	.47026							2	4
.82252	.52581	.27105	.66334	2.1163	4.5304	5.9642	8.3495	3	4
1.0023	1.0033	1.0036	1.0199	1.1558	1.4978	1.7002	2.0393	4	4
1.0028	1.0048	1.0052	1.0205	1.0867	1.2301	1.3243	1.4964	5	4
1.0025	1.0039	1.0042	1.0147	1.0568	1.1410	1.1964	1.2888	6	4
1.0021	1.0029	1.0031	1.0107	1.0401	1.0967	1.1346	1.1958	7	4
1.0019	1.0025	1.0026	1.0085	1.0294	1.0848	1.1070	1.1542	8	4
1.0010	1.0016	1.0017	1.0064	1.0313	1.0615	1.0826	1.1402	9	4
1.0008	1.0014	1.0015	1.0052	1.0222	1.0518	1.0712	1.1071	10	4
1.0011	1.0014	1.0015	1.0047	1.0184	1.0449	1.0620	1.0917	11	4
1.0008	1.0012	1.0013	1.0043	1.0165	1.0399	1.0550	1.0807	12	4
1.0009	1.0012	1.0013	1.0040	1.0147	1.0358	1.0494	1.0726	13	4
1.0012	1.0013	1.0013	1.0037	1.0134	1.0323	1.0449	1.0658	14	4
1.0012	1.0013	1.0013	1.0035	1.0124	1.0296	1.0411	1.0599	15	4
1.0009	1.0012	1.0012	1.0034	1.0114	1.0270	1.0370	1.0556	16	4

HELIUM LIGUID AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)

.0002626	.0002626	.0002626	.0002626	.0002626	.0002626	.0002626	.0002626	1	4
	.0003005	.0003005	.0003005	.0003005	.0003005	.0003005	.0003005	2	4
		.0001467	.0004503	.0009079	.0022293	.0033147	.0055733	3	4
		.0003080	.0003212	.0003447	.0003696	.0003813	.0003960	4	4
		.0005133	.0005133	.0005163	.0005192	.0005199	.0005236	5	4
		.0007612	.0007612	.0007612	.0007612	.0007612	.0007612	6	4
		.0010795	.0010795	.0010795	.0010795	.0010795	.0010795	7	4
		.0013977	.0013977	.0013977	.0013977	.0013977	.0013977	8	4
		.0017160	.0017160	.0017160	.0017160	.0017160	.0017160	9	4
		.0020343	.0020343	.0020343	.0020343	.0020343	.0020343	10	4
		.0023525	.0023525	.0023525	.0023525	.0023525	.0023525	11	4
		.0026708	.0026708	.0026708	.0026708	.0026708	.0026708	12	4
		.0029891	.0029891	.0029891	.0029891	.0029891	.0029891	13	4

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                .0033073 .0033073 .0033073 .0033073 .0033073 .0033073  14   4
                .0036256 .0036256 .0036256 .0036256 .0036256 .0036256  15   4
                .0039439 .0039439 .0039439 .0039439 .0039439 .0039439  16   4
HELIUM VAPOR AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)
 .0000704                                                               1   4
 .0000632 .0000949                                                      2   4
 .0000647 .0000868 .0001467 .0004503 .0009079 .0022293 .0033147 .0055733  3   4
 .0002977 .0003043 .0003080 .0003212 .0003447 .0003696 .0003813 .0003960  4   4
 .0005133 .0005133 .0005133 .0005133 .0005163 .0005192 .0005199 .0005236  5   4
 .0007612 .0007612 .0007612 .0007612 .0007612 .0007612 .0007612 .0007612  6   4
 .0010795 .0010795 .0010795 .0010795 .0010795 .0010795 .0010795 .0010795  7   4
 .0013977 .0013977 .0013977 .0013977 .0013977 .0013977 .0013977 .0013977  8   4
 .0017160 .0017160 .0017160 .0017160 .0017160 .0017160 .0017160 .0017160  9   4
 .0020343 .0020343 .0020343 .0020343 .0020343 .0020343 .0020343 .0020343 10   4
 .0023525 .0023525 .0023525 .0023525 .0023525 .0023525 .0023525 .0023525 11   4
 .0026708 .0026708 .0026708 .0026708 .0026708 .0026708 .0026708 .0026708 12   4
 .0029891 .0029891 .0029891 .0029891 .0029891 .0029891 .0029891 .0029891 13   4
 .0033073 .0033073 .0033073 .0033073 .0033073 .0033073 .0033073 .0033073 14   4
 .0036256 .0036256 .0036256 .0036256 .0036256 .0036256 .0036256 .0036256 15   4
 .0039439 .0039439 .0039439 .0039439 .0039439 .0039439 .0039439 .0039439 16   4
HYDROGEN TEMPERATURE VECTOR (DEG. R.)
   36.5      1                                                             2
   46.8      2                                                             2
   52.4      3                                                             2
   56.4      4                                                             2
   59.4      5                                                             2
  100.0      6                                                             2
  180.0      7                                                             2
  270.0      8                                                             2
  360.0      9                                                             2
  450.0     10                                                             2
  540.0     11                                                             2
  630.0     12                                                             2
  720.0     13                                                             2
  810.0     14                                                             2
  900.0     15                                                             *
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990.0 16

HYDROGEN PRESSURE VECTOR (PSIA) 2

14.69	1	2
58.76	2	2
102.8	3	2
146.9	4	2
187.7	5	2
587.6	6	2
1028.0	7	2
1469.0	8	2

HYDROGEN LIQUID AND SUPERCRITICAL ENTHALPY DATA (BTU/LB) 2

109.93	108.17	106.92	105.67	104.46	92.61	79.09	65.43	1	2
	-79.49	-78.32	-77.75	-76.89	-68.47	-56.76	-44.25	2	2
		-56.24	-56.35	-56.00	-52.57	-42.56	-30.88	3	2
			-32.40	-33.05	-39.41	-31.05	-20.26	4	2
				52.08	-29.21	-22.38	-12.22	5	2
				245.27	199.70	166.30	152.66	6	2
				462.40	446.52	433.37	424.63	7	2
				931.02	926.44	923.15	921.74	8	2
				1215.25	1215.65	1217.61	1219.78	9	2
				1513.55	1517.35	1521.74	1526.74	10	2
				1819.99	1825.28	1831.52	1838.13	11	2
				2129.39	2135.97	2143.44	2150.92	12	2
				2440.53	2447.92	2456.30	2464.68	13	2
				2752.34	2760.29	2769.31	2778.34	14	2
				3064.42	3072.85	3082.42	3092.00	15	2
				3376.77	3385.53	3395.47	3405.42	16	2

HYDROGEN VAPOR AND SUPERCRITICAL ENTHALPY DATA (BTU/LB)

81.79									
116.97	88.12							1	2
125.24	108.80	82.69						2	2
135.47	121.22	102.92	71.77					3	2
142.77	129.69	113.98	93.13	52.08	-29.21	-22.38	-12.22	4	2
265.67	260.44	255.18	249.91	245.27	199.70	166.30	152.66	5	2
470.01	467.98	465.98	464.01	462.40	446.52	433.37	424.63	6	2
935.36	932.73	932.10	931.49	931.02	926.44	923.15	921.74	7	2
								8	2
									*

1215.28	1215.25	1215.22	1215.21	1215.25	1215.65	1217.61	1219.78	9	2
1512.50	1512.83	1513.17	1513.51	1513.55	1517.35	1521.74	1526.74	10	2
1817.79	1818.35	1818.90	1819.45	1819.99	1825.28	1831.52	1838.13	11	2
2126.32	2127.05	2127.78	2128.50	2129.39	2135.97	2143.44	2150.92	12	2
2437.07	2437.89	2438.71	2439.54	2440.53	2447.92	2456.30	2464.68	13	2
2748.56	2749.46	2750.36	2751.27	2752.34	2760.29	2769.31	2778.34	14	2
3060.42	3061.37	3062.32	3063.28	3064.42	3072.85	3082.42	3092.00	15	2
3372.54	3373.56	3374.58	3375.59	3376.77	3385.53	3395.47	3405.42	16	2

HYDROGEN LIQUID AND SUPERCRITICAL COMPRESSIBILITY DATA

.01697	.06755	.1175	.1672	.2128	.6396	1.0901	1.4901	1	2
	.05989	.1035	.1460	.1851	.5390	.8985	1.2415	2	2
		.1044	.1450	.1829	.5098	.8374	1.1470	3	2
			.1595	.1998	.5245	.7788	1.0555	4	2
				.3303	.7427	.7572	1.0240	5	2
				.9524	.8594	.8613	.9394	6	2
				1.0119	1.0027	1.0219	1.0557	7	2
				1.0235	1.0262	1.0509	1.0793	8	2
				1.0230	1.0279	1.0508	1.0757	9	2
				1.0210	1.0259	1.0465	1.0678	10	2
				1.0189	1.0236	1.0414	1.0603	11	2
				1.0169	1.0211	1.0370	1.0537	12	2
				1.0152	1.0187	1.0324	1.0481	13	2
				1.0140	1.0170	1.0299	1.0435	14	2
				1.0126	1.0153	1.0272	1.0398	15	2
				1.0116	1.0146	1.0251	1.0363	16	2

HYDROGEN VAPOR AND SUPERITICAL COMPRESSIBILITY DATA

.9048								1	2
.9516	.7695							2	2
.9641	.8390	.6623						3	2
.9705	.8710	.7483	.5547					4	2
.9734	.8892	.7880	.6533	.3303	.7427	.7572	1.0240	5	2
.9950	.9818	.9687	.9559	.9524	.8594	.8613	.9394	6	2
.9994	.9968	.9930	.9881	1.0119	1.0027	1.0219	1.0557	7	2
1.0001	1.0021	1.0035	1.0060	1.0235	1.0262	1.0509	1.0793	8	2
1.0007	1.0024	1.0042	1.0065	1.0230	1.0279	1.0508	1.0757	9	2
1.0004	1.0025	1.0039	1.0062	1.0210	1.0259	1.0465	1.0678	10	2

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1.0063	1.0021	1.0035	1.0056	1.0189	1.0236	1.0414	1.0603	11	2
1.0001	1.0018	1.0027	1.0049	1.0169	1.0211	1.0370	1.0537	12	2
1.0000	1.0014	1.0027	1.0044	1.0152	1.0187	1.0324	1.0481	13	2
1.0000	1.0013	1.0022	1.0041	1.0140	1.0170	1.0299	1.0435	14	2
1.0000	1.0012	1.0022	1.0037	1.0126	1.0153	1.0272	1.0398	15	2
1.0060	1.0099	1.0019	1.0031	1.0116	1.0146	1.0251	1.0363	16	2

HYDROGEN LIQUID AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)

.0011450	.0011450	.0011450	.0011450	.0011450	.0011450	.0011450	.0011450	1	2
	.0012750	.0012750	.0012750	.0012750	.0012750	.0012750	.0012750	2	2
		.0013433	.0013433	.0013433	.0013433	.0013433	.0013433	3	2
			.0013917	.0013917	.0013917	.0013917	.0013917	4	2
				.0006108	.0015882	.0020154	.0022902	5	2
				.0004703	.0005961	.0007659	.0009186	6	2
				.0007763	.0008330	.0008965	.0009928	7	2
				.0011813	.0012164	.0012625	.0012827	8	2
				.0014369	.0014505	.0014778	.0014846	9	2
				.0016328	.0016391	.0016455	.0016519	10	2
				.0018393	.0018504	.0018615	.0018738	11	2
				.0020432	.0020462	.0020528	.0020559	12	2
				.0022800	.0022800	.0022800	.0022800	13	2
				.0025350	.0025350	.0025350	.0025350	14	2
				.0027900	.0027900	.0027900	.0027900	15	2
				.0030300	.0030300	.0030300	.0030300	16	2

HYDROGEN VAPOR AND SUPERCRITICAL THERMAL CONDUCTIVITY DATA (BTU/MIN.FT.DEG. R.)

.0001506								1	2
.0001920	.0002628							2	2
.0002112	.0002532	.0003144						3	2
.0002268	.0002502	.0002808	.0003480					4	2
.0002358	.0002640	.0002826	.0003174	.0006108	.0015882	.0020154	.0022902	5	2
.0004154	.0004263	.0004373	.0004593	.0004703	.0005961	.0007659	.0009186	6	2
.0007340	.0007402	.0007518	.0007641	.0007763	.0008330	.0008965	.0009928	7	2
.0011277	.0011472	.0011609	.0011731	.0011813	.0012164	.0012625	.0012827	8	2
.0013790	.0013879	.0013947	.0014138	.0014369	.0014505	.0014778	.0014846	9	2
.0015817	.0015945	.0016073	.0016200	.0016328	.0016391	.0016455	.0016519	10	2
.0017949	.0018072	.0018165	.0018319	.0018393	.0018504	.0018615	.0018738	11	2
.0020372	.0020390	.0020462	.0020414	.0020432	.0020462	.0020528	.0020559	12	2
									*

.0022800	.0022800	.0022800	.0022800	.0022800	.0022800	.0022800	.0022800	13	2
.0025350	.0025350	.0025350	.0025350	.0025350	.0025350	.0025350	.0025350	14	2
.0027900	.0027900	.0027900	.0027900	.0027900	.0027900	.0027900	.0027900	15	2
.0030300	.0030300	.0030300	.0030300	.0030300	.0030300	.0030300	.0030300	16	2

Appendix D

List of Variables

C -Conductivity, BTU/°R, min., ft.

CAP -A vector whose elements are thermal capacitances, BTU/°R

CCT -Variable for enthalpy interpolation, BTU/lb

CDATA (J, I) -A matrix whose element in row J, column I, is the conductivity at temperature TEM(J) and pressure PR(I), BTU/min. °R., ft.

CNDR -A vector whose elements are conductor values, BTU/min. °R

COP -Partial derivative of conductivity with respect to temperature

COT -Partial derivative of conductivity with respect to pressure

CP -Partial derivative of enthalpy with respect to temperature

CS -Total capacity of solid nodes, BTU/°R

CT -Partial derivative of enthalpy with respect to pressure

DELP -Pressure differential for heater control, psia, heater is off when pressure exceeds PMAX + DELP and on when pressure is lower than PMAX - DELP

DELT -Mixed temperature increase corresponding to time step DETEE, °R

DM -Working variable

DENSE -A vector whose I^{th} element is the fluid density, lb./cu. ft., at node I at the previous computing step

DETEE -Computing increment, min.

DOSX -A vector whose elements mark times at which fluid supply rate changes, see input instructions

DP -Difference in pressure between columns in data table

DPDT -Rate of pressure change, psi/min.

DT -Difference in temperature between rows in data table

DTIM -Computing increment when heater is on

DTIME -Computing increment except as above

EMZERO	-Fluid mass at beginning of time step, lb.
EONE	-Total energy of all fluid nodes, BTU
ERP	-Initial mass, lb.
F	-Variable for density interpolation
FLOW	-A vector whose elements are flow rates between nodes, lb/min.
FOLD	-Working variable
FLUX	-Total heater rating, BTU/min
FR	-Density, lb/cu.ft.
H	-Enthalpy, BTU/lb.
HDATA (J, I)	-A matrix whose element in row J, column I is the enthalpy at temperature TEM(J) and pressure PR(I), BTU/lb.
HL	-Saturated liquid enthalpy at PZERO, BTU/lb.
HTWO	-Enthalpy of the system at two phase boundary, BTU/lb.
HV	-Saturated vapor enthalpy at PZERO, BTU/lb.
HZERO	-Average initial enthalpy, BTU/lb.
IP	-Index parameter for print out
IRMA	-Number of solid nodes
IT	-Number of computing steps between print out for pressure rise and venting operation
JACK	-A vector whose elements are conductor numbers, a zero element is used to distinguish between conductors attached from one node and those attached to another
JAN (I)	-Vector such that the I^{th} element is a node connecting conductor I
JILL	-A vector whose elements are node numbers -- if there are N conductors and M nodes in a problem, there will be 2N + M elements in JACK and JILL
JIM (I)	-Vector such that I^{th} element is a node connecting conductor I
JIP	-Integer variable
JUNK	-IRMA + 1

KIM	-Number of radiation conductors
LILY	-LULU + 1
LINDA	-Interpolation variable
LISA	-Number of fluid conductors
LISP	-Number of elements in STIR vector
LOLA	-LULU + LISA + 1
LOLITA	-A vector used to distinguish between solid and fluid nodes -- the first IRMA elements are all the solid node numbers
LORA	-Number of elements in JACK vector
LP	-Number of computing steps between print out for supply portion of operation
LUCY	-LULU + LISA
LULU	-Number of solid conductors
LYDIA	-Number of fluid nodes
MABEL	-Variable used to control exit from instructions which compute ZSAZSA
MANCHA	-Indexing variable of the STIR vector
MANDY	-Node number having ZSAZSA
MWT	-Stored fluid molecular weight
NAN	-Variable used to distinguish between mass transfer operations -- NAN is negative implies the mass flow terms are included in the energy equation, otherwise the mass flow terms are neglected
NCNDR	-Total number of conductors
NODES	-Total number of nodes
P	-The pressure, psia, used by the DATA subroutine for computing density, compressibility, enthalpy and conductivity
PC	-Critical pressure, psia
PEMAX	-Pressure in psia at which both fluid supply and venting occur
PMAX	-Supply pressure, psia

POLD	-Pressure at preceding computing step, psia
PR	-A vector whose elements are pressure, psia, for example PR(I) gives the pressure corresponding to column I of the enthalpy table
PSAVE	-Pressure in system before mixing, psia
PTWO	-Pressure of the system at two phase boundary, BTU/lb.
PUFF	-A vector whose elements mark times at which input heat leak changes, see input instructions
PZERO	-Pressure at filling, psia
QDOT	-Actual heater output, BTU/min.
QIN (I)	-Fraction of input heat leak entering node I
QLEAK	-Input heat leak, BTU/min.
QS (I)	-Fraction of total heater input entering node I
RB	-Variable for density interpolation, lb./cu. ft.
RC	-Gas constant, psia, cu. ft./lb., °R
RHO	-Average density, lb./cu. ft.
RHOC	-Critical density, lb./cu. ft.
RHOT	-Density, lb./cu. ft.
RO	-Density, lb./cu. ft.
ROLD	-Density, lb./cu. ft.
ROSA	-A vector whose elements are fluid supply rates, see input instructions
RP	-Variable for density interpolation, lb./cu. ft., °R
RS	-Gas constant, BTU/lb. °R
RT	-Variable for density interpolation, lb./cu. ft. psi
R1	-Variable for density interpolation, lb./cu. ft.
R2	-Variable for density interpolation, lb./cu. ft.
R3	-Variable for density interpolation, lb./cu. ft.

SLOPE	-Slope of a line
SOLD	-Working variable
SOURCE	-A vector giving total heat input contribution from heat leak, heater output, pressure change, BTU/min.
SPOT	-A vector whose elements are heat leak rates, see input instructions
ST	-Time necessary to bring the system from an initial fill having two phases to a single phase condition, min.
STIR (I)	-This vector gives mission times at which stored fluid is to be mixed, min.
SUM	-Working variable
SUMF	-Cumulative heater output, BTU
SUMK	-Sum of conductor values attached to a node, BTU/min., °R
SUMKT	-Sum of products of conductor values and temperatures for a node, BTU/min.
SUMV	-Cumulative fluid vented during supply time
SUSIE	-Option parameter -- see input instruction list
T	-The temperature, °R, used by the DATA subroutine for computing density, compressibility, enthalpy and conductivity
TC	-Critical temperature, °R
TEM	-A vector whose elements are temperature, °R. For example TEM(J) gives the temperature corresponding to row J in the enthalpy table
TEMP	-A vector whose elements are node temperatures, °R
THALP	-A vector whose elements are enthalpy, BTU/lb
TIMAX	-Time in min. used to stop program
TIME	-Lapsed time since filling, min.
TONE	-Temperature of the system at two phase boundary, °R
TP	-Mixed fluid temperature, °R
TSTAR	-An interpolated saturation temperature, °R
TTWO	-Time for fluid supply, measured from fill time, min.

TZERO	-Saturated temperature at PZERO, °R
U	$-\Delta t \sum K_{ji}/CAP(I)$, dimensionless
VENT	-Mass vented during one time step in supply operation, lb.
VOL (I)	-A vector such that element I is the volume of fluid node I
VOLUME	-Total stored fluid volume, cu. ft.
XMWT	-Stored fluid molecular weight in floating point form
XNDR	-Conductor coefficient, for fluid conductors this is transport area divided by conductor path length, ft., but for radiation conductors it is the product of the Stefan Boltzmann constant, area, and view factor, BTU/min., $°R^4$
Z	-Compressibility factor
ZAP	-Exit mass rate, lb./min.
ZASS	-Stored fluid mass, lb.
ZDATA (J,I)	-A matrix whose element in row J, column I, is the compressibility factor at temperature TEM(J) and Pressure PR(I)
ZDOT	-Fluid supply rate, lb./min.
ZILCH	-An intermediate variable used in the DATA subroutine
ZIQMAS	-Liquid phase mass at fill time, lb.
ZP	-Partial derivative of Z with respect to temperature
ZSAZSA	-Maximum value of computing increment times sum of conductors divided by capacity
ZT	-Partial derivative of Z with respect of pressure.

Appendix E

Derivation of the Energy Equation

The energy equation simply assumes that input minus output is accumulation. Because of the small velocities involved, the neglect of kinetic energy seems justified. Thus the equation is

$$V_i \frac{d(\rho_i E_i)}{dt} = \dot{m}_{i-1} E_{i-1} + \frac{\dot{Pm}_{i-1}}{\rho_{i-1}} + \dot{q}_{i-1,i} - \dot{m}_i E_i - \frac{\dot{Pm}_i}{\rho_i} - \dot{q}_{i,i+1} + F_i \qquad \text{(E-1)}$$

On the left side of (E-1) is the rate of energy accumulation in volume element i. The $\dot{m}E$ terms account for bulk flow between elements while the terms containing P represent work associated with moving mass into or out of volume elements. The q terms account for conductive heat flow. The F term represents input heat, as from an external leak or a heater. Next the left side of (E-1) may be expanded using the law for differentiation of a product

$$V_i \left[\rho_i \frac{dE_i}{dt} + E_i \frac{d\rho_i}{dt}\right] = \dot{m}_{i-1} H_{i-1} + \dot{q}_{i-1,i} - \dot{m}_i H_i - \dot{q}_{i,i+1} + F_i \qquad \text{(E-2)}$$

The second term on the left side of (E-2) may be replaced by (8) to give

$$V_i \rho_i \frac{dE_i}{dt} = \dot{m}_{i-1} (H_{i-1} - E_i) + \dot{m}_i (E_i - H_i) + \sum_j \dot{q}_{ji} + F_i \qquad \text{(E-3)}$$

The dependent variables of most interest are pressure and temperature and these may be introduced by the following relations.

$$E = H = ZRT \tag{E-4}$$

$$\frac{dE}{dt} = \frac{dH}{dt} = RZ\frac{dT}{dt} = RTZ_P\frac{dT}{dt} = RTZ_T\frac{dP}{dt} \tag{E-5}$$

$$\frac{dH}{dt} = C_P\frac{dT}{dt} + C_T\frac{dP}{dt} \tag{E-6}$$

Introducing (E-4), (E-5) and (E-6) into (E-3) leads to the following expression for the energy equation.

$$V_i\rho_i\left(C_P - RZ - RTZ_P\right)\frac{dT_i}{dt} = \sum_j \dot{q}_{ji} + F_i + \dot{m}_{i-1}\left(H_{i-1} - H_i + ZRT_i\right) - \dot{m}_i ZRT_i - V_i\rho_i\left(C_T - RTZ_P\right)\frac{dP}{dt} \tag{E-7}$$

The above is the same as (16) in the main text.